VOLCANIC HAZARDS FROM FUTURE ERUPTIONS OF AUGUSTINE VOLCANO. ALASKA

by

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ABSTRACT

Augustine Volcano, located on an uninhabited island in lower Cook Inlet, has erupted 5 times since 1812, the first documented eruption after the discovery in 1778. Augustine is one of the most active volcanoes in the eastern Aleutian arc. Constancy of eruptive style, volume, and geochemistry has characterized the eruptions, suggesting that the feeding magma reservoir has not changed significantly during its very young eruptive history - the volcano is probably less than about 15,000 years old. Eruptions are typically Peléean, beginning with powerful vent clearing eruptions and ending with new dome intrusions. Hot pyroclastic flows are common during both stages, the first stage producing column collapse pyroclastic flows (Soufrière type), the second stage dome collapse pyroclastic flows (Merapi type). Pyroclastic flow deposits make up the bulk of the volcanic island and extend at least 4 km offshore.

The dominant hazard near the volcano on and offshore are pyroclastic flows and fast moving hot gas and dust clouds (nuées ardentes). Prevailing westerly high altitude winds govern the ash dispersal of the eruptions predominantly to the east-northeast affecting all of the Cook Inlet region (including the west shore), the Kenai Peninsula and the Gulf of Alaska. During one eruption the volcano has produced a tsunami which crossed lower Cook Inlet to the Kenai Peninsula.

INTRODUCTION

Mount St. Augustine is a very young symmetrical island volcano in Lower Cook Inlet, southern Alaska, 285 km southwest of Anchorage and 100 km west-southwest of Homeron the lower Kenai Peninsula (Figure 1). The channel that separates the island from the west shore of Cook Inlet is 10 km wide at its narrowest point. The circular island has a diameter of about 12 km and from its center rises a single symmetrical cone about 1,200 meters high. The island is uninhabited, however, from 1946 to 1949 pumice was mined on its southwest flank for use as a lightweight aggregate for construction materials (Moxham, 1951). The nearest population centers are on the Kenai Peninsula, 100 km across Cook Inlet, and at Lake Iliamna, 90 km north-northwest. There is a road from Iliamna Bay, 30 km north-northwest of the volcano, to Pile Bay on Iliamna Lake, sometimes used to portage small boats from Cook Inlet into the Lake Iliamna drainage. Otherwise, Kamishak Bay has no permanent population except for floating canneries or freezer barges during the summer fishing season.

Augustine is part of the Aleutian volcanic arc which spans 3000 km between Kamchatka and mainland Alaska. The arc is the result of convergence of the North American and Pacific lithospheric plates. The Cook Inlet volcanoes Spurr, Redoubt, Iliamna, Augustine and Doug"las are nearly perfectly aligned along the strike of a very active deep seismic zone marking the site of plate subduction in Cook Inlet.

The bulk, if not all of the visible cone of Augustine, has formed in post-glacial times, perhaps as recent as 19,000 to 15,500 years ago (Johnston, 1979a). In the past 200 years since the discovery and naming of the volcano on May 20, 1778 by James Cook on his third Pacific voyage

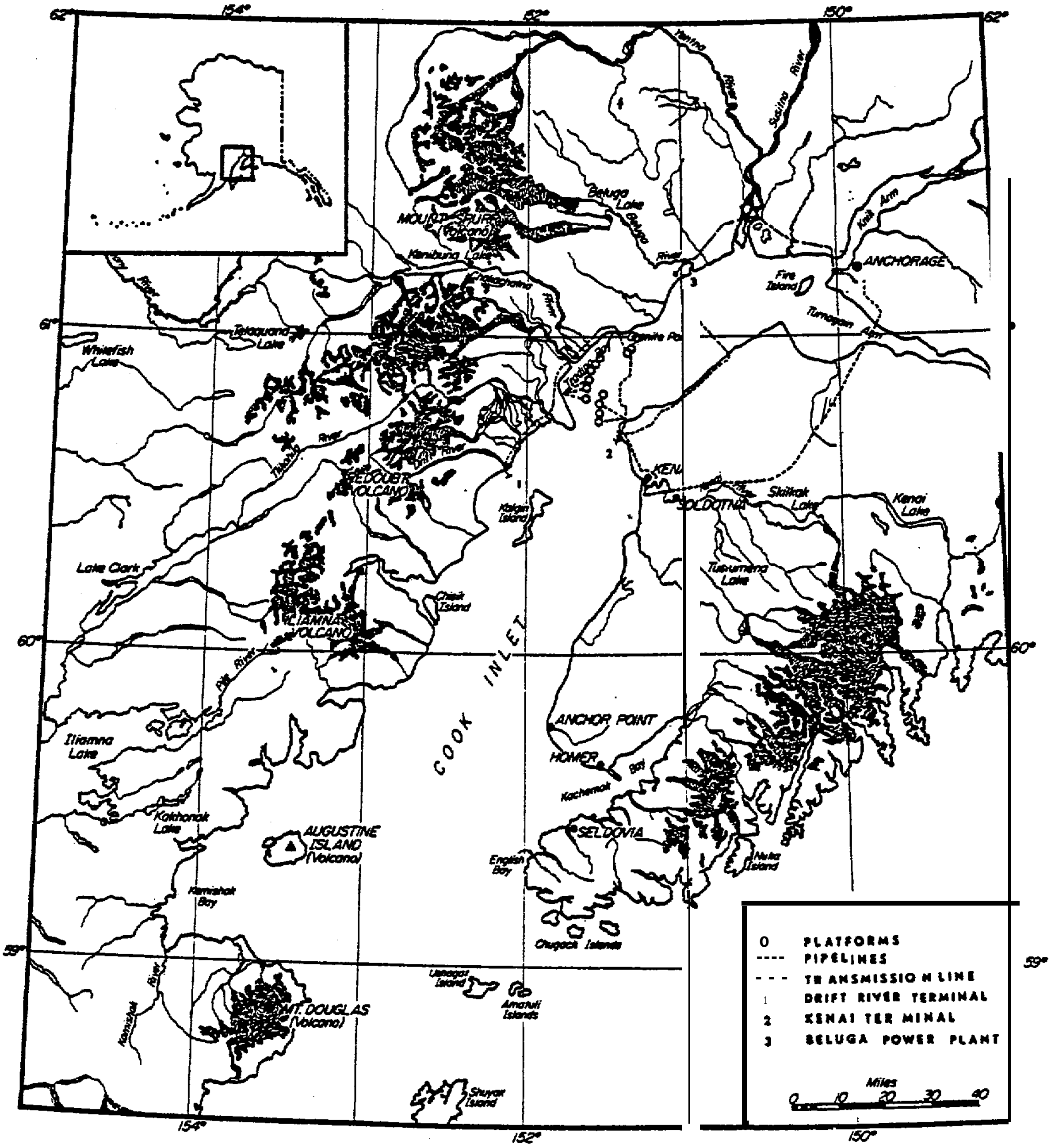


Figure 1. Location of Cook Inlet Volcanoes, settlements, oil pipelines and platforms.

(Beaglehole, 1967) Augustine has had 5 significant eruptions: 1812, 1883, 1935, 1963/64 and 1976 (Doroshin, 1870; Davidson, 1884; Detterman 1968, Kienle and Forbes, 1976; Johnston, 1978). Based on the historic record, it appears that all recent Augustine eruptions were Peléean and each greatly modified the appearance of the volcano. Typically, viscous dome intrusions ended the eruptive cycles and dome collapse produced extensive pyroclastic avalanche deposits. This style of highly explosive activity coupled with the island setting, youthfulness and short recurrence rate of eruptions make Augustine the most hazardous volcano in Cook Inlet. There is no reason to believe that similar eruptions will not occur again.

If one assumes that Augustine's eruptive style will remain that of the past 200 years, an assumption which seems reasonable based on the remarkably uniform chemistry of the eruptive products, the principal near field hazards will be pyroclastic avalanches, mudflows, glowing clouds {which can continue out to sea) and heavy bomb and ash falls. Assuming that there wil 1 never be any industrial development on the island, explosive eruptions characteristic of Augustine present hazards to lower Cook Inlet communities, to the fishing industry, to major water and air travel routes to Anchorage and, if oil development gets underway near Augustine, to offshore petroleum drilling and production platform (Johnston et al., 1977, see also Figure 2). The principal hazard in the far field, potentially affecting inhabitants on the Kenai Peninsula and in the Iliamna Lake region, will be heavy ashfalls, muddy and acid rains, and possibly tsunamis at the shores of Cook Inlet as during the 1883 eruption.

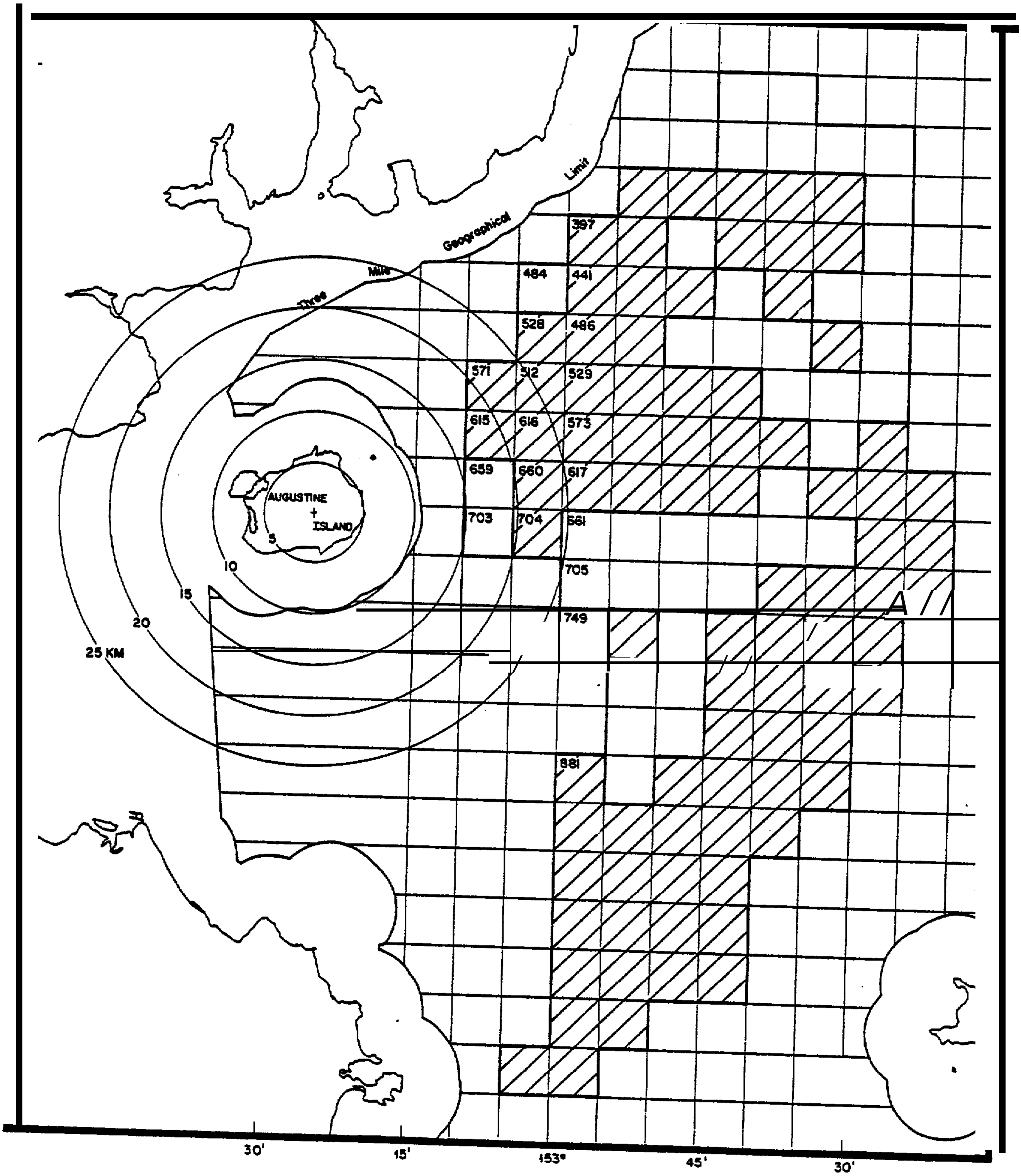


Figure 2. Location of Augustine Volcano in relation to already sold leases (cross hatched).

ERUPTIVE HISTORY

Prehistoric

Augustine is a very young volcanic center, most likely post-glacial . in age. The volcanic cone is built upon an uplifted basement of Jurassic, Cretaceus and Tertiary sandstones, siltstones and shales (Detterman, 1973; Buffler, 1976 and 1980), probably heavily zeolitized at shallow depth beneath the volcano, as indicated by high seismic velocities (Kienle et al., 1979). On the southern flank of the volcano southward dipping uplifted section of marine sediments crops out at elevations up to about 300m and is overlain by a thin layer of glacial debris and boulders (Detterman, 1973; Buffler 1976). Johnston (1979a) described a stratigraphic section on the south side of the volcano between the 260 and 320 m level that might date the onset of volcanism at Augustine. The section consists of principally non-volcanic preglacial lake deposits with layers of pumice-rich sands and basaltic hyaloclastites, implying that the initial Augustine eruptions were rhyolitic-basaltic and volcanism began while this lake existed. Because exotic glacial boulders are concentrated at the unconformable interface between the sediments and the lake deposits and because the level of occurrence of glacial debris correlates with dated shorelines at about the 230 m level in eastern Cook Inlet, Johnston deduced that the preglacial lake must have existed during the Moosehorn glacial advance. The onset of volcanism at Augustine is thus dated at 17,000 to 13,500 years B.C.

The lake deposits are horizontally layered unconformably overlying the south-dipping Mesozoic sandstones and shales which indicates that the uplifting of the basement, presumably due to intrusive activity prior to the onset of extrusive volcanism, occurred prior to the deposition of the lake sediments (Buffler, 1980). Johnston (1979a), quoting other workers (Plafker, 1965; Detterman and Reed, 1973; and Karlstrom, 1964) thought that an additional 45 to 90 m of uplift may have occurred since Moosehorn times, assuming modern and recent uplift rates of 0.3-0.6 m/century.

Extensive areas of prehistoric mudflow and pyroclastic flow deposits occur on the lower eastern and western flanks of the volcano, and also up to at least 4 km offshore all around the island. Two C^{14} dates from a soil horizon that directly overlies the seacliff forming mudflow deposits on the eastern flank of the volcano give a minimum age for these flows of 1500 ± 155 and 1470 ± 160 years B.P.

The distribution of prehistoric deposits on Augustine Island is shown on Figure 3. Most of the older deposits on Augustine Island are buried by younger ejects. However, around the margins of the island older deposits can be identified. The inferred distribution shown on Figure 3 revises the map by Detterman (1973) and is based on photo interpretation of newer aerial photography.

Discovery

The volcano was discovered on Saint Augustine's day (May 26) by Captain James Cook in 1778 on his third Pacific voyage (Figure 4). He named it Mount St. Augustine[1] and described it as "of a conical figure and of a very considerable height" (Beaglehole, 1967). Other early descriptions also corroborate the conical shape of the mountain topped by a "rounded dome without a peak" (Dan, 1884) and "presenting nearly

[1]Map makers later omitted the "Saint"

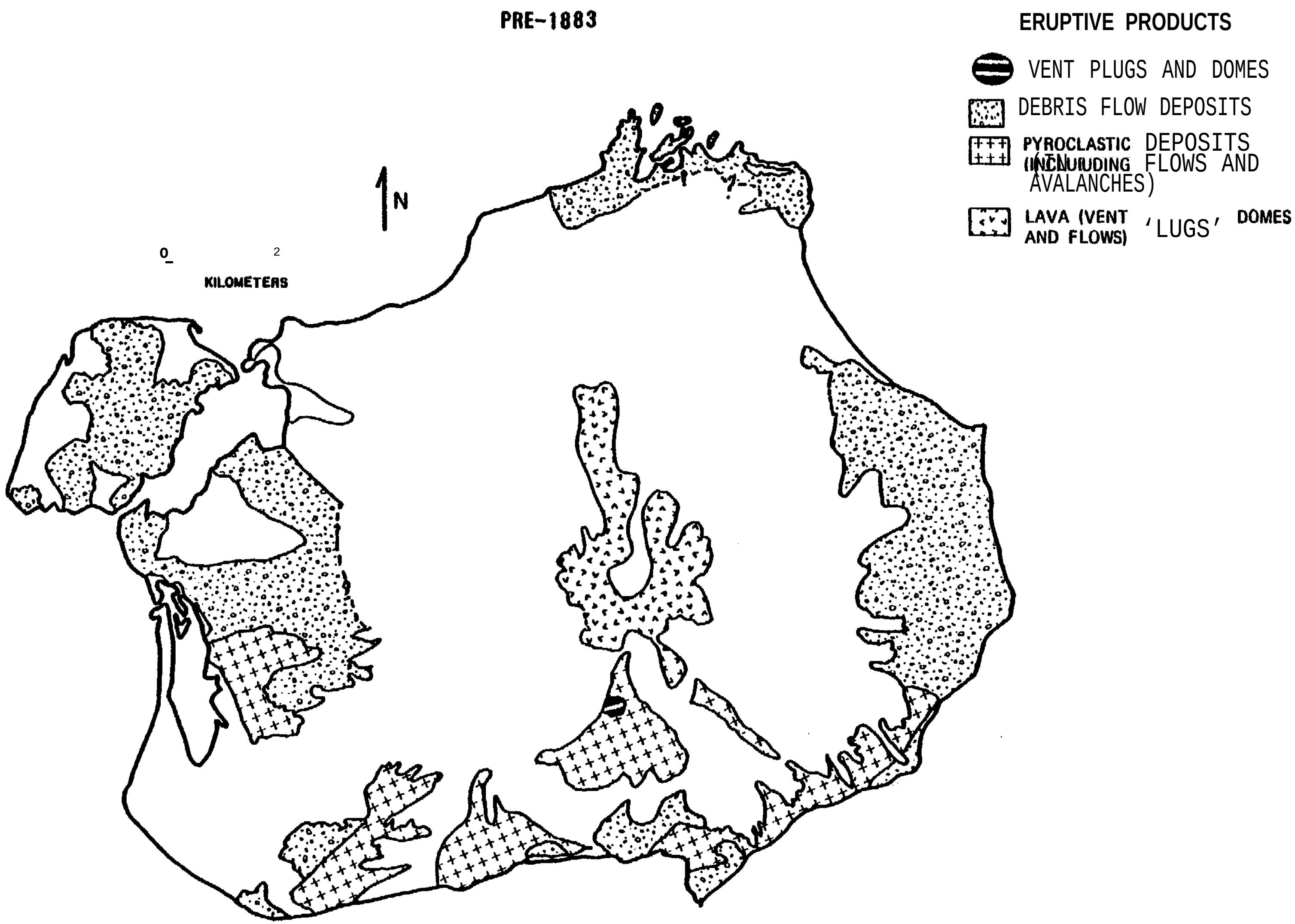
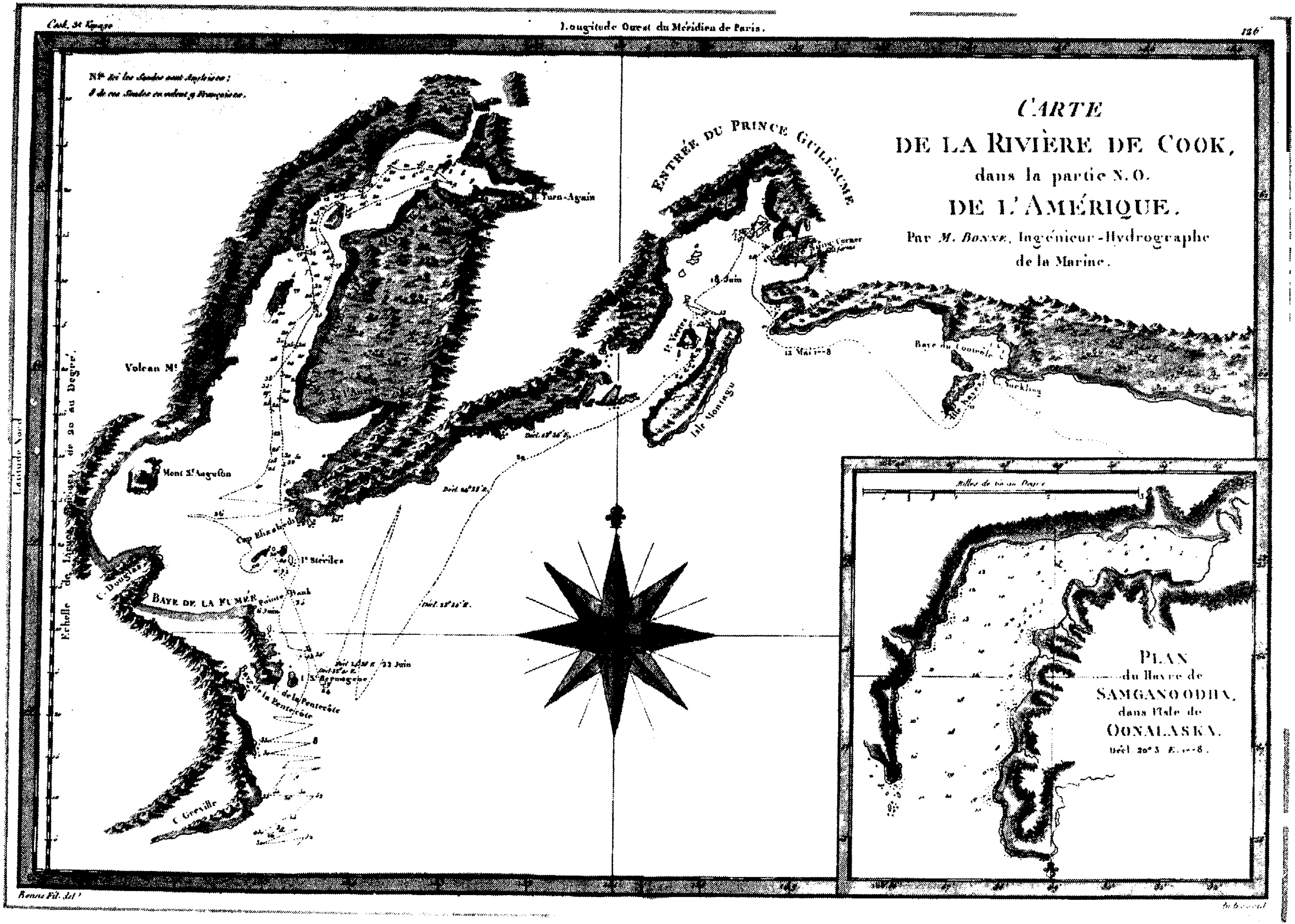


Figure 3 Distribution of pre-1883 eruptive products.



F gure 4. D scovery by Captain Cook, May 26 St. Augustine's Day , 778.

the **same appearance from every point of view" (Davidson, 1884, quoting Captain Puget's description of 1794).** This "rounded dome" was most likely an early vent plug (Kienle and Forbes, 1976).

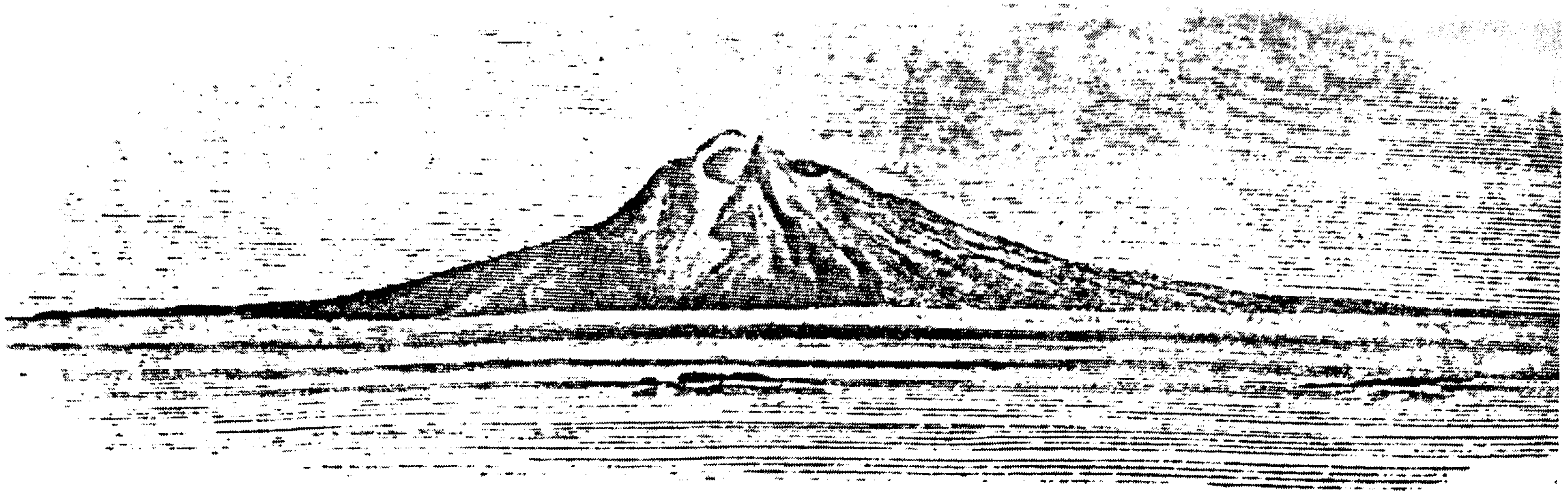
1812 Eruption

Doroshin (1870) describes Chernabura[2] (Augustine) as an "irregular cone with a rounded peak consisting of lava and pumice". Figure 5 (top) is a sketch of the volcano as seen from the north, given in Doroshin's publication. The sketch is remarkably similar to the first photograph we have of the volcano taken in 1909 from the same direction (Figure 5, bottom), except that the drawing shows a spine nonvisible in the 1909 photograph. That spine was probably destroyed in the 1883 eruption.

Doroshin (1870) reports that the volcano "burned" in 1812, "as was positively confirmed bya native of the village located in the opposite shore of the Bay [he is referring to Kenai Bay, i.e. Cook Inlet; the village could be English Bay on the lower Kenai Peninsula]. It wasn't possible to reach the island . . . . because the lava [pyroclastic flows?], half of which had flown into the sea, could at any time rend the skin of the baidarkas (canoe)".

We *surmise* that prior to 1812 Augustine's summit was occupied by a large lava dome giving the volcano the overall rounded symmetrical appearance described by the early Pacific explorers, Cook and Puget. This dome was apparently destroyed in the 1812 eruption resulting in a *new* summit crater breached to the north which was only partially filled by a new dome intrusion with a pronounced summit spine (Figure 5, top). During the vent clearing eruptions in 1812, ash dispersed 210 km north-

[1]Chernabura, a local corruption of the Russian name (Ostrov) Chernoburoy, meaning "black-brown" (island) - Orth (1967); other spellings found in the literature are Chernobour, Chonoborough, Chernaboura, Tchernybura and probably others.



Островъ Чернобурый.

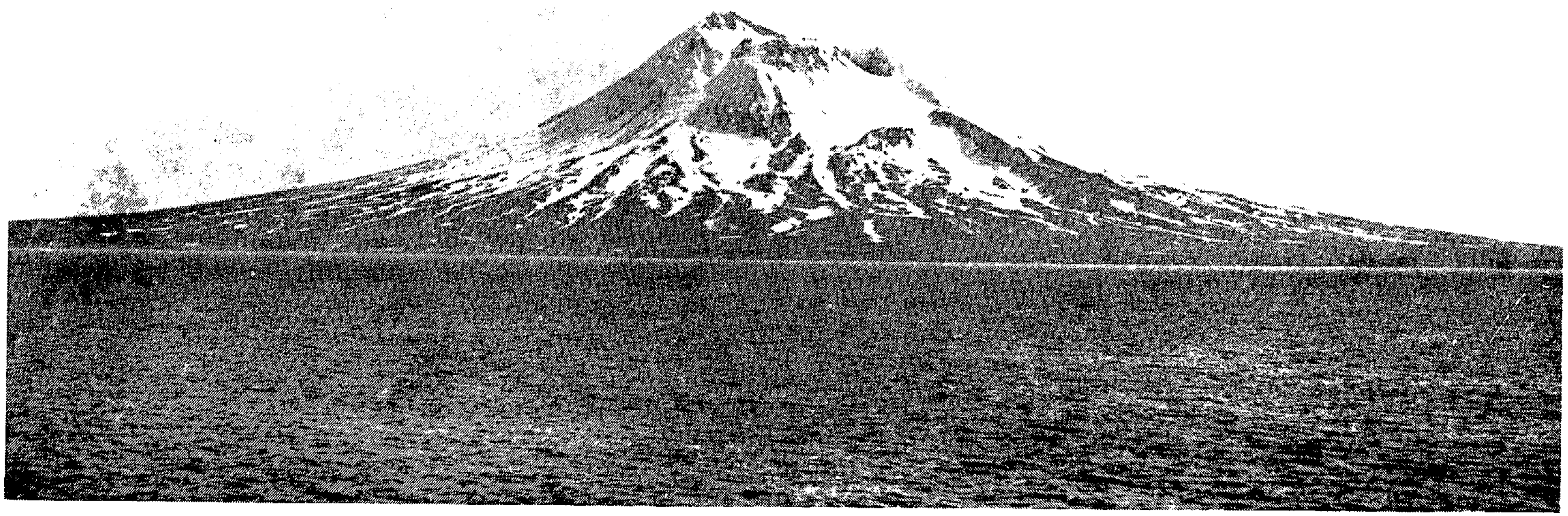


Figure 5. Top: Sketch of Augustine Volcano as seen from the north, pre-1883 and post-1812 eruptions (Doroshin, 1870). Bottom: 1909 photograph from the north showing that the dome and spine occupying the crater prior to 1883 was probably exploded and replaced by a new dome intrusion in 1883.

east to Skilak Lake, as evidenced-by an ash layer found by Rymer and Sims (1976) in the varved lake deposits. The ash is dated by counting the varves.

In 1880 Mount St. Augustine had a height of 3,800 feet (1,158 m) "as measured by angles from different stations" (Dan, 1884).

1883 Eruption

On the morning of October 6, 1883 Augustine burst again into violent eruption. Dan (1884) stated that smoke first arose from the volcano in August about two months before the cataclysmic eruptions of October 6. The initial eruption was vividly described by Davidson (1884):

"About eight o'clock of the morning of October 6, 1883, the weather being beautifully clear, the wind light from the south-westward (compass), and the tide at dead low water, the settlers and fishing-parties at English Harbor[3] heard a heavy report to windward. When the heavy explosion was heard vast and dense volumes of smoke were seen rolling out of the summit of St. Augustine and moving to the north-eastward (or up the inlet... At the same time (according to the statements of a hunting-party of natives in Kamishak Bay) a column of white vapor arose from the sea near the island, slowly ascending, and gradually blending with the clouds. The sea was also greatly agitated and boiling, making it impossible for boats to land upon or leave the island.. .From English Harbor (Port Graham) it was noticed that the columns of smoke, as they gradually rose, spread over the visible heavens, and obscured the sky, doubtless under the influence of a higher current (probably north or northeast). Fine pumice-dust soon began to fall, but gently, some of it being very fine, and some very soft, without grit... Twenty-five minutes after the great eruption, a great 'earthquake wave', estimated as from twenty-five to thirty feet high, came upon Port Graham like a wall of water. It carried off all the fishing-boats from the point, and deluged the houses. This was followed,. at intervals of about five minutes, by two other large waves, estimated at eighteen and fifteen feet; and during the day several large and irregular waves came into the harbor. The first wave took all the boats into the harbor, the receding wave swept them back again to the inlet, and they were finally stranded. Fortunately it was low water, or all the people at the settlement must inevitably have been lost. The tides rise and fall about fourteen feet."

Based on the annual report of the Russian Orthodox Missionary at Kenai, dated May 28, 1884, the waves generated by the eruption may have reached other shores of Cook Inlet:

[3]Near Port Graham Inlet, 85 km east of the volcano across Cook Inlet.

> "Influenza Kenai, Ninilchik, Seldovia, Alexandrovsky (English Bay), nearly all children up to 2 years of age were swept away. At the same time this region suffered from inundation caused by the eruption of Chernabura Volcano which is about 60 miles across strait from Alexandrovsky. The inundation so frightened the natives of Alexandrovsky that they moved their huts to higher ground in one night".

According to Davidson (1884), the sea waves were also felt at Kodiak and the "pumice-ashes" accumulated to a depth of "4 to 5 inches" (10 to 13 cm).

From the description of dense smoke "rolling out" from Augustine's summit, a column of white vapor rising from the sea near the island and the sea being greatly agitated and boiling we deduce that during the October 6 eruptions a large hot pyroclastic flow must have rushed down the slope of the volcano and impacted into the shoal waters surrounding Augustine Island. The sudden displacement of large volumes of sea water probably gave rise to the waves that crossed Cook Inlet to English Bay. The most likely place of impact was the north or northeast shore of Augustine near Burr Point where we find the freshest terrain on the island. Whether or not the Burr Point terrain itself was created in 1883 is not clear, as there are no records of photographs that document the topography or shoreline of the north side of the island prior to the 1883 eruption. The sparse vegetation and fresh appearance of the hummocky topography do suggest that the Burr Point terrain is relatively young but perhaps a little older than 1883. We have submitted organic soils overlying the Burr Point lahar for C^{14} dating to resolve this question. If Burr Point turns out to be older than 1883, the October 6 flow most likely impacted on the northeastern shoreline of the island, An alternate explanation for the sea waves, though less likely than impact of a pyroclastic flow, could be that they were true tsunamis, i.e., generated by the sudden displacement of the sea floor due to earthquake or other volcanic activity. Davidson, however, does not report any seismic disturbance on October 6 - except for using the term 'earthquake wave'.

Following the October 6 eruption, flames issuing from the summit of Augustine could be seen at night from English Bay while during the day vast volumes of smoke were seen "rolling" from it. The rolling motion of the cloud and incandescence during the night implies that pyroclastic flow and nuée ardente activity continued for a considerable time, probably affecting all flanks of the volcano, even though a path down the existing north-northeastern breach was most likely.

Davidson (1884) also reports that the volcano had ruptured from east to west with substantial subsidence of the northern half of the island and that a new island had formed northwest of the island, based on statements made by Captain Sands and Captain Cullie, who approached Augustine Island on November 10 on the schooner Kodiak. Apparently these statements were corroborated by a native party which hunted in Kamishak Bay during the eruptions, but studying Figure 5 (bottom) and the offshore bathymetry of Augustine Island we cannot find evidence for such major morphologic changes of the volcano. Perhaps a large floating mass of pumice was mistaken to be an island; the alledged subsidence of the northern half of the island seems to be an exaggeration of Captain Cullie (Becker, 1898).

Augustine volcanic activity must have continued for over a year after the outbreak of 1883, as interpreted from another entry in the Kenai mission log on May 27, 1885:

"Earthquakes still quite frequent here (Kenai?) and Chernabura is still smoking."

A very important narrative of the 1883 eruption which also makes reference to strong earthquake activity and tidal waves during the eruptions comes from a recently discovered field notebook from 1898 of the pioneering U.S. Geological Survey geologist, J. A. Spurr. The notebook is now in the USGS archives in Menlo Park, California:

October 17, (1898)

"Trader says here at Katmai that eighteen years ago three families from Kodiak went with families and baidarkas to St. Augustine Island to spend the winter. Built barabaras on the shore of a bay. The mountain began to shake continually and finally they took their families off, while they stayed on themselves.[4] Finally the mountain began to shake so violently that they put all their effects in their baidarkas and started on a stormy day. Scarcely were they at the mouth of the bay when an explosion occurred, ashes, boulders and pumice began pouring down and the barabaras were buried and the bay filled up with debris. At the same time there were many tidal waves, so that the natives nearly perished with fright, yet finally escaped."

As to the dispersal of tephera from this eruption, ash from the morning eruption on October 6 accumulated to a depth of "1/4 inch" (6 mm) at English Bay (Alaska Commercial Company Records, English Bay Daily Logs, Archives, University of Alaska) and a "rain of ashes" commenced again at 11 a.m. lasting all day. Even though a considerable amount of ash seems to have fallen at Kodiak, according to Davidson (1884) (4 to 5 inches (10 to 13 cm), no ash was found in the Skilak Lake sediments (Rymer and Sims, 1976), suggesting that the wind disperal direction was mainly east-southeasterly.

[4] The occupation and evacuation of Augustine Island by these families is also mentioned by Davidson (1884); the eruption must have been that of October 6, 1883, rather than 1880, as suggested by Spurr's reference to "18 years ago" as related by the trader.

When Becker and Purington (Becker 1898) made the first ascent of Augustine Volcano on July 22, 1895, they discovered a crater at least "1,200 feet" (370 m) in diameter with a nearly vertical inner wall, showing well-developed columnar jointing and breached to the north. An unstable inner "cone" (dome?) occupied the crater, steaming from countless crevices and separated from the outer walls by a "600 or 800 feet" (180 or 240 m) deep moat. The inner cone was nearly as high as the outer crater wall and rock avalanches frequently broke off thundering into the surrounding moat. Solfataric action blanched and reddened the surface of the cone. Figure 6 shows one of the two U.S. Geological Survey geologists, Becker or Purington, in the summit crater of Augustine, probably in 1895. Their description of the inner cone suggest that the cone was not a cinder cone as they implied but a still hot degassing vent plug. They also believed that the lava flow that can be seen in Figure 5 formed in 1883, which is clearly a misinterPretation since the flow is drawn on the sketch published by Doroshin in 1870 (Figure 5, top).

Deposits from the 1883 eruption are shown on Figure 7. The distribution of the 1883 ejects is mapped primarily from aerial photography taken of Augustine Island in 1957. On these photographs, the most recent volcanic deposits are from the 1935 eruption while the older but still discernible, volcanic flows (debris and pyroclastics) are taken to represent the 1883 eruption. The main thrustof the debris flows of this eruption was to the north-northeast.

1902 Event

Coats (1950, quoting Sapper 1927), Detterman (1973, referring to unpublished field notes of T. W. Stanton of the U.S. Geological Survey .

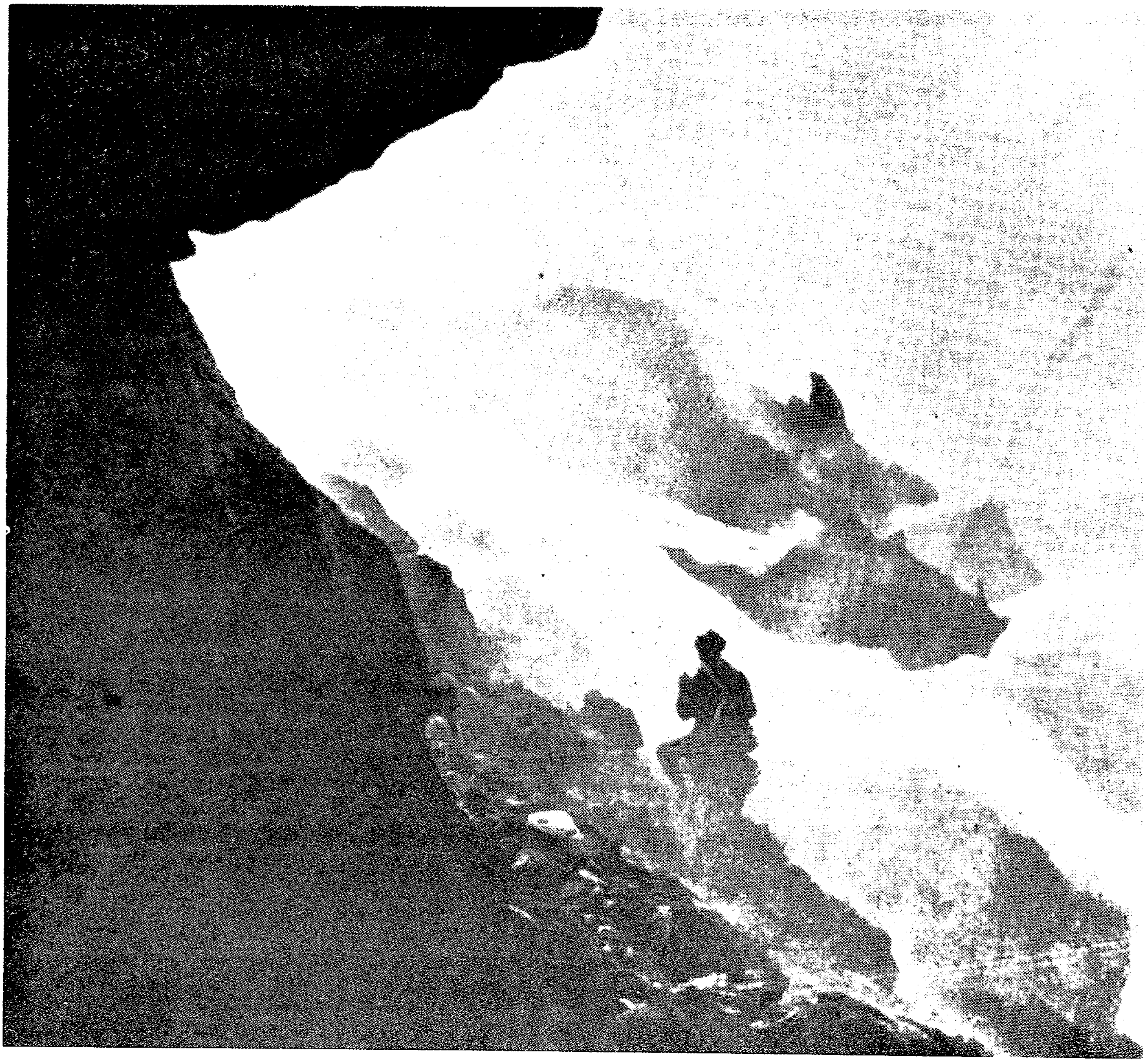


Figure 6. Crater of Augustine showing central dome in 1895 (USGS geologist is probably Becker or Purington).

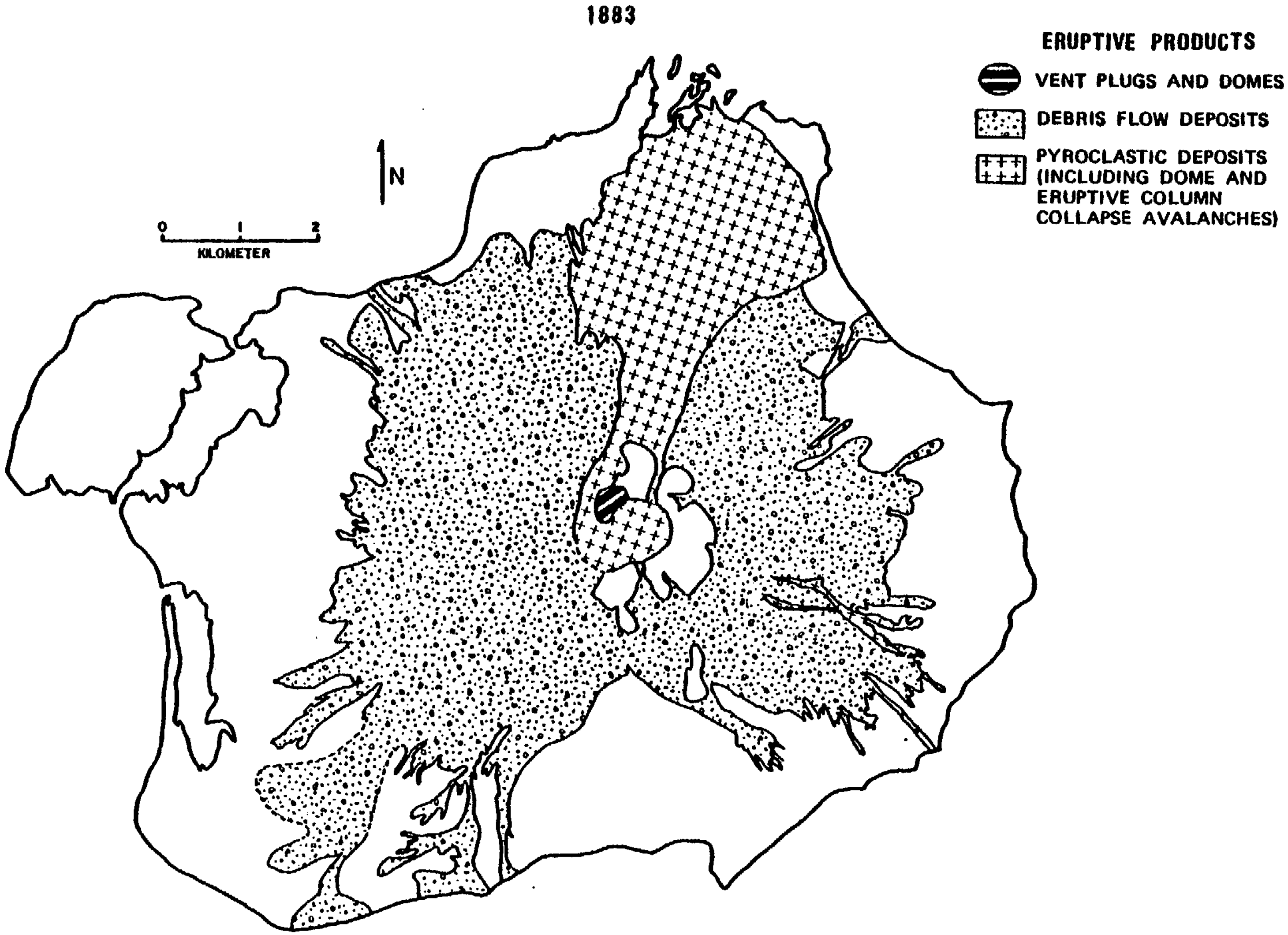


Figure 7. Distr bution of 1883 eruptive products.

who visited Augustine Island on July 17, 1904) and Kienle and Forbes (1976, quoting the previous sources) report a minor phreatic explosion, partial destruction of the north crater rim accompanied by a large mudflow, and finally new dome growth and formation of a spire in 1902. Johnston (1979b) carefully reviewed the original notes and old photographs and concluded that Augustine did not have a significant eruption in 1902, except perhaps for "a large mudflow [generated] when one side of the crater broke off and slipped down, according to A. Brown who says he witnessed it from the mainland" (Stanton's field notes). Johnston (1979b) also could not identify an ash layer on Augustine Island that would correspond to a major eruption in 1902.

1935 Eruption

Detterman (1973) reports that the eruption started on March 13 and ended August 18. In mid-August a tall black eruption cloud, 10 to 30,000 feet (3 to 9 km) high, rather thin and not billowing outat the top was seen by Mr. Wahleen (personal communication) from aboard the S. S. Dellwood just after leaving False Pass on a great circle route to Seattle. Since no other eastern Aleutian volcano was active that year, it seems that Mr. Wahleen saw the final major eruption of Augustine Volcano on August 18, from a distance of about 800 km! Between March and August, minor and major eruptions were also observed from the west side of Cook Inlet. Considerable amounts of tephra were erupted, and pyroclastic flows and mudflows were concentrated on the northeastern and southwestern flanks of the volcano (Detterman, 1973; Figure 8). The 1883 dome described by Becker (1895) was presumably destroyed during the initial vent clearing eruptions, when ash spread again as far as Skilak Lake (Rymer and Sims, 1976). Finally, two new lava domes were emplaced

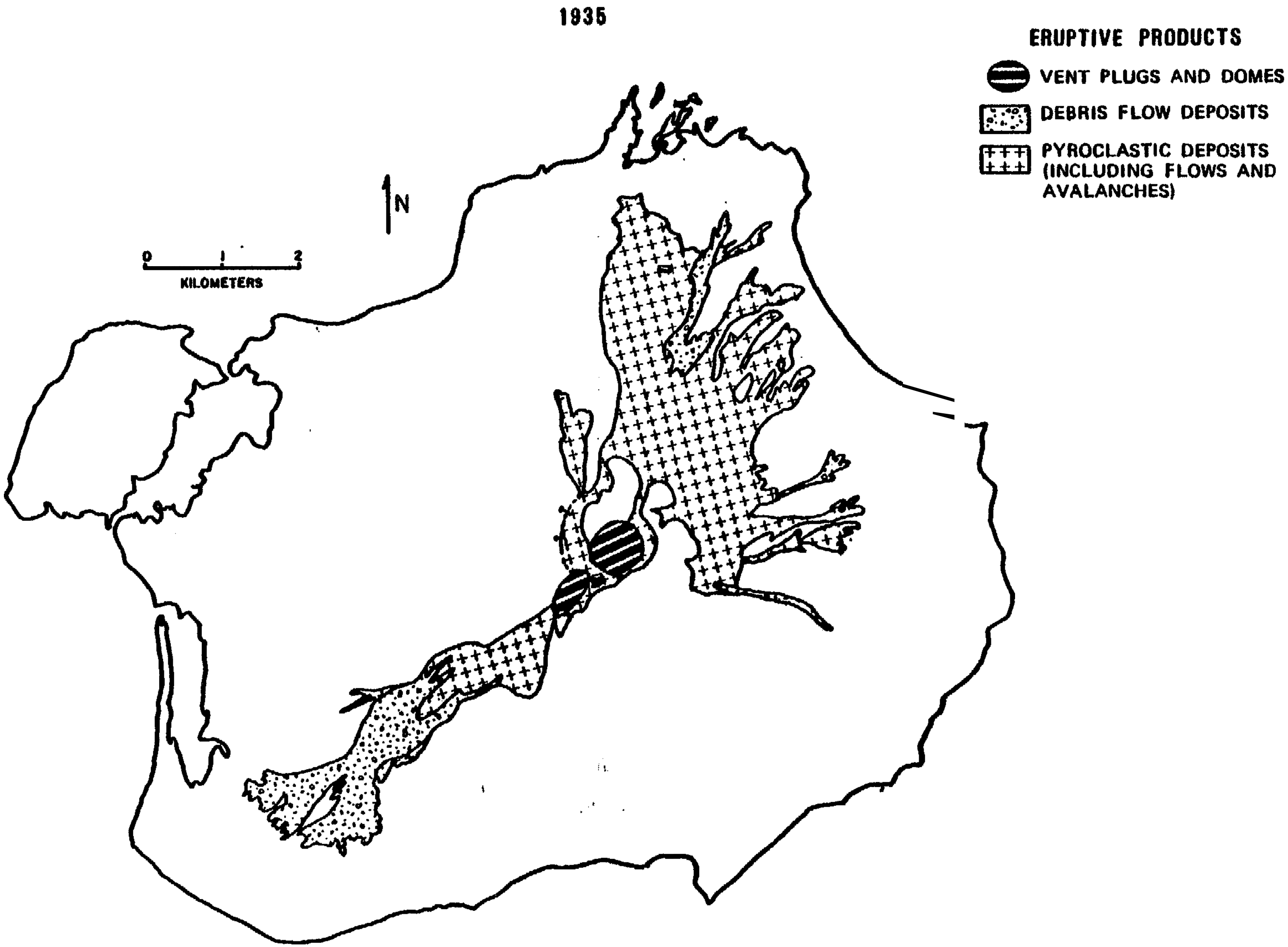


Figure 8. Distribution of 935 eruptive products.

in the summit crater. The summit forming dome was a nearly perfect dacite tholoid, 4,025 feet high (1227 m), as determined photogrammetrically (USGS 1: 63,360 quadrangle map, Iliamna, B-2, Alaska). Thus by late 1935 the volcano had increased 498 feet (152 m) in height since DalI's first survey in 1880.

Deposits from the 1935 Augustine eruption are shown on Figure 8. Data for this figure are taken from 1957 aerial photography where the youngest volcanic features are considered to represent the 1935 eruption. The two domes emplaced during the last stages of the 1935 eruption are apparent on the aerial photographs and are also shown on Figure 8.

1963/64 Eruption

On October 11, 1963, Augustine burst into activity again, sending an ash column to about 3,000 m and a pyroclastic flow down the flank of the volcano, which set fire to brush on the lower slopes. According to Detterman (1968), the eruption continued intermittently for about 10 months, with major explosions recorded on November 17, 1963, July 5 and August 19, 1964. Presumably, during one or more of the earlier vent clearing eruptions in late 1963 ash was dispersed in a northeasterly direction and preserved in the varved sediments of Skilak Lake, 210 km distant (Rymer and Sims, 1976). Figure 9 shows an eruption photographed by Tom Hazard of the Bureau of Land Management on July 7, 1964 aboard an aircraft at 3,000 m elevation, 60 to 80 km northeast of the volcano. The eruption column reaches to about 3.5 km and tephra can be seen precipitating out of the cloud over the southwestern flank of the volcano. Many other such eruptions probably went unnoticed as there is no winter population on the shores of Kamiskak Bay and the nearest settlements are on the Kenai Peninsula, 100 km across Cook Inlet.

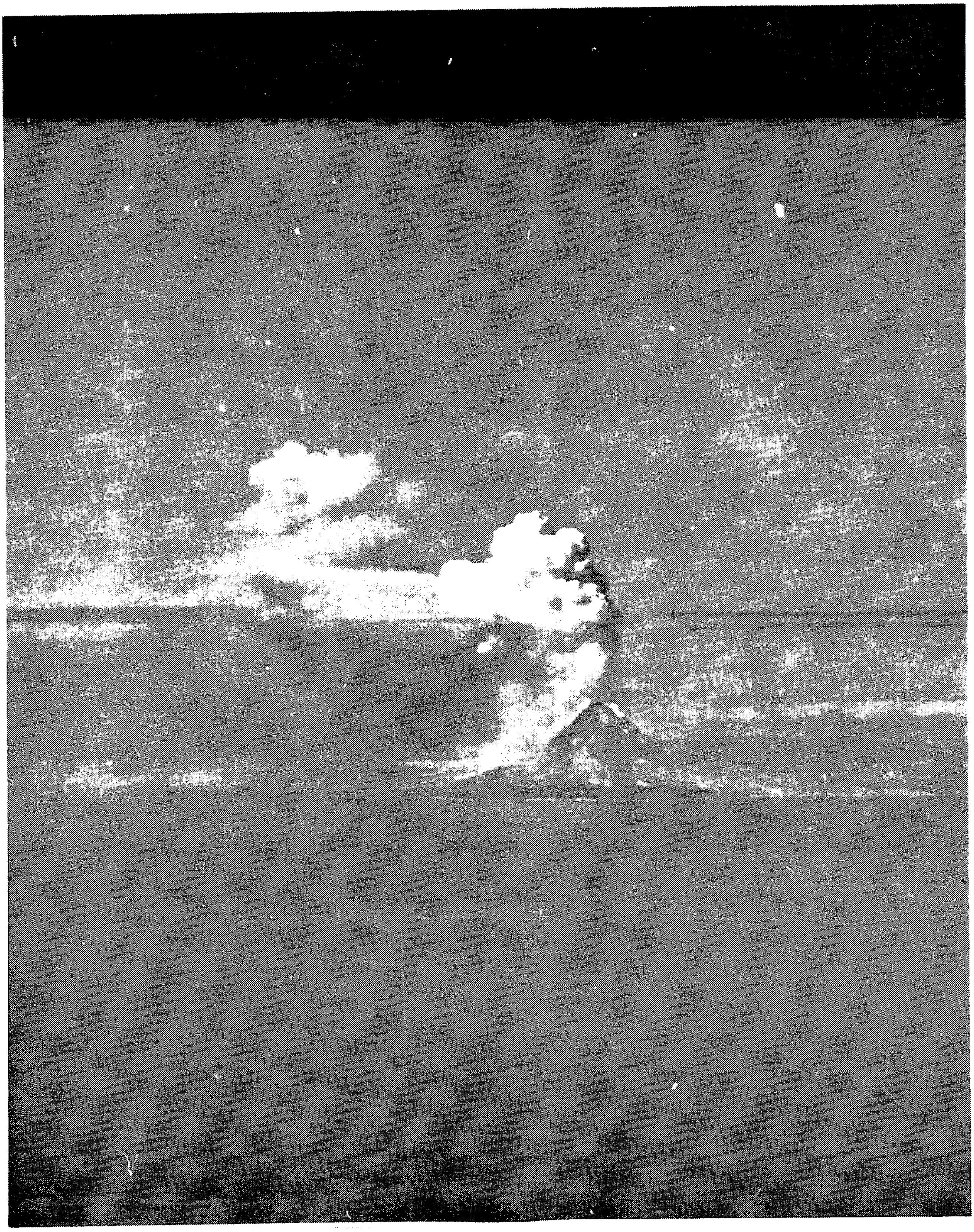


Figure 9. Augustine Volcano in eruption, July 7, 1964, as seen from the northeast (photograph by T. Hazard, BLM).

According to reports from field parties of the Pan American Petroleum Corporation (D.H. Reno, communication to R. B. Forbes) there was no unusual precursor activity during the summer 1963 field season, which terminated mid-July, but in the June-July 1964 field season the volcano was reported to be quite active and considerable ash was encountered on the mountains on the mainland up to 15 km west of Augustine. Where the ash was not disturbed it was a maximum of about 2.5 cm deep.

Detterman (1968) reports that the cone emitted smoke and steam all through 1965 and 1966, before he actually visited the island to map the deposits of the 1963/64 eruption in 1967. Detterman thought that the initial eruption was a nuee ardente eruption directed toward the southeast and originating at the base of the 1935 summit tholoid. It allegedly blew out a section of crater wall "3,200 feet long, 500 feet high and 700 feet thick".

The 1963/64 eruptions greatly altered the summit configuration and finally a new dome emerged in the new crater southeast of the remnant of the 1935 summit tholoid. By September 1964 (Figure 10) it had completely filled the crater, engulfed what was left of the eastern and southern crater rim and stood much higher than the original 1935 summit. A new summit elevation of 4,304 feet (1312 m) was determined geodetically in 1971 for the summit forming spine on top of this 1964 dome by the National Ocean Survey (J.E. Guth, written communication). Thus, at the end of the 1963/64 eruptive cycle the volcano had again increased in height by 279 feet (85 m) as compared to 1935.

The 1964 dome is an excellent example of an endogenous dome formed by internal expansion. The resulting structure is a series of inverted

Figure 10. Augustine's summit from the northeast in 1971. The 1935 and '64 lava domes are marked, P (Pinnacles) are erosional remnants of a vent breccia, L is a short lava flow.

nested cones forming concentric moats and ridges on the surface. Much of the gas released during the cooling of the dome was released along this concentric conical fracture system.

Distribution of the 1963/64 eruptive deposits (Figure 11) is largely taken from Detterman (1968). In 1963/64 debris flows were mainly directed north, southwest and southeast. One area of Figure 11 does differ from Detterman's results and is the region occupied by the volcanic dome. The dome area shown on Figure 11 is taken from numerous photographs of . the summit region between 1964 and 1976 and probably is a better representation than that given by Detterman (1968).

1971 Event

Continuous instrumental observation of Augustine Volcano began in late 1970, when the Geophysical Institute of the University of Alaska installed a radio-telemetered, vertical, short-period seismic station on its upper northern flank. Since 1970, this single station has been expanded to a 4 station island-based array and we have continuous seismic data since 1970. The only significant seismic activity prior to the precursor seismicity observed in 1975 before the 1976 eruption was an intense earthquake swarm that occurred between August 30 and September 6, 1971 (Kienle et al., 1971). The earthquakes originated within the central conduit system of the cone above sea level (Lana, 1980) and were signaling a minor eruption. A photograph taken during the swarm by Austin Post of the U.S. Geological Survey on September 3 shows a strong plume fed by very active fumaroles on the 1964 lava dome (Figure 12). A' small ash eruption and incandescence (red glow) on the flank of the volcano was seen during the late evening twilight of October 7 from a fishing boat 38 km north of the volcano. The eruption is corroborated

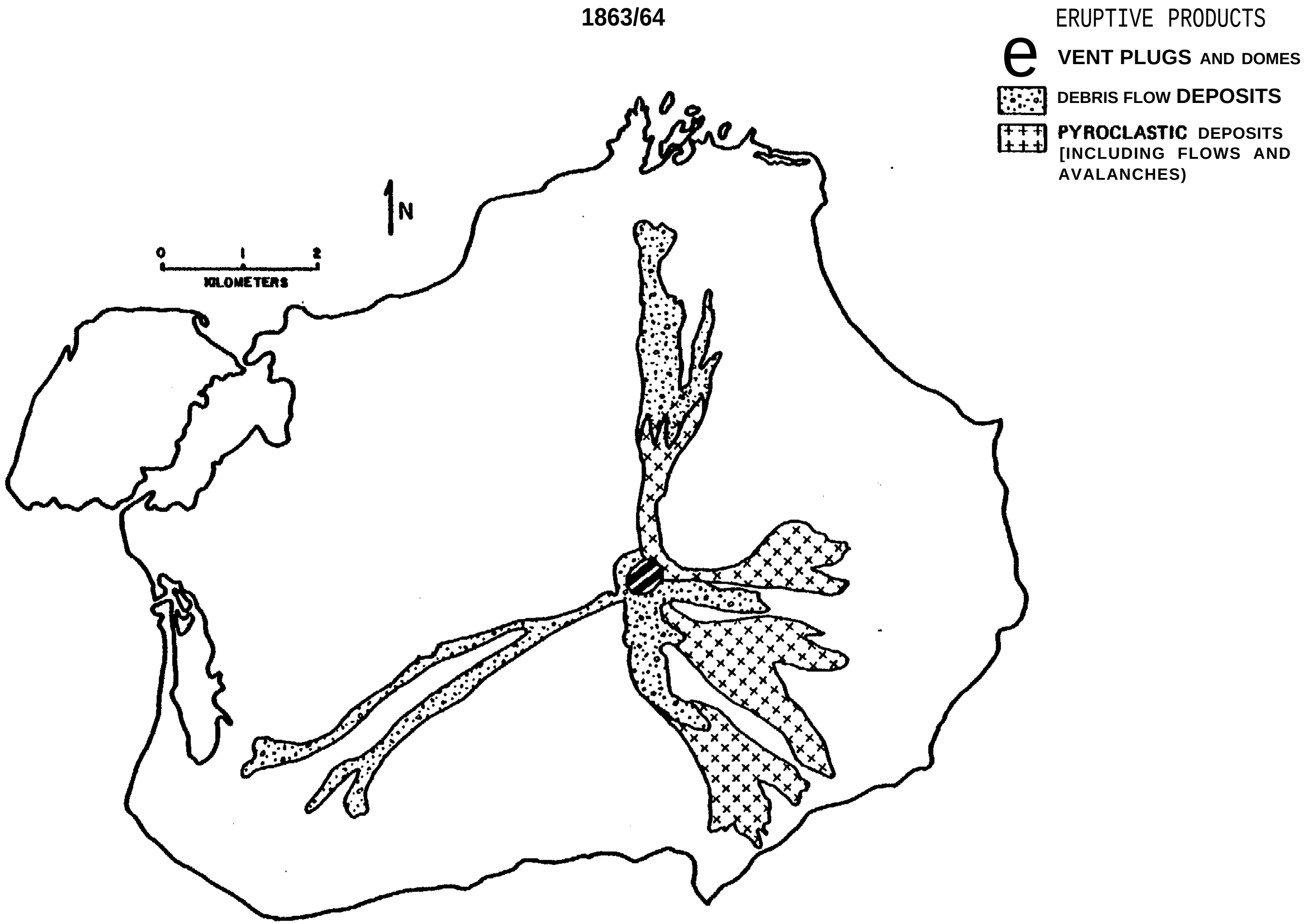


Figure 11. Distribution of 1963/64 eruptive products.

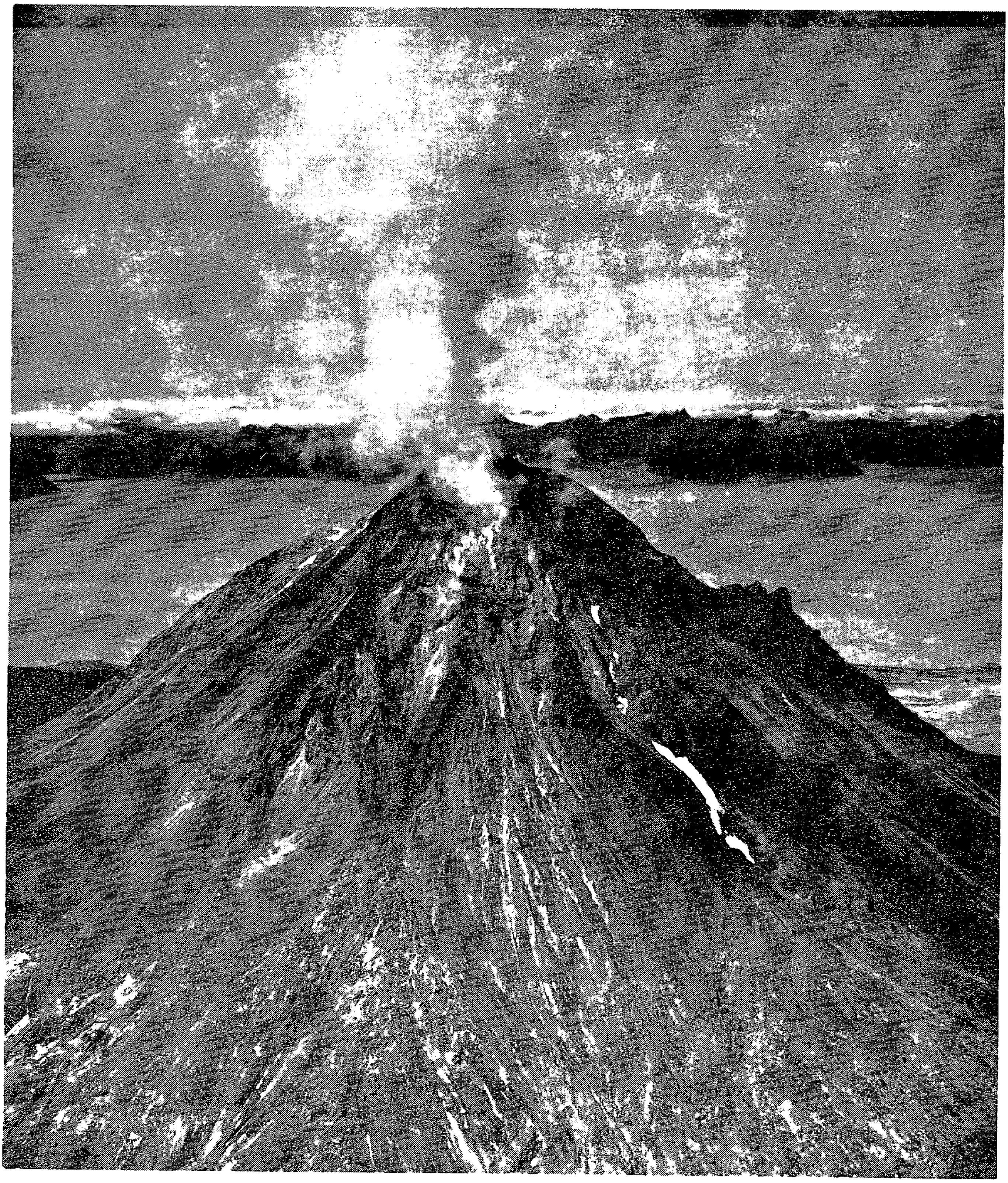


Figure 12. Augustine Volcano from the south on September 3, 1971. A strong vapor plume is being fed by fumaroles on the 1964 dome during a period of intense swarms of shallow earthquake activity (photograph by Austin Post, USGS).

by seismic eruption tremor, which was recorded on both of the then existing seismic stations between 23 and 01 hours on October 7/8.

1976 Eruption

This eruption is fairly well documented because we had intensified our geophysical surveillance of the volcano in the years prior and kept close track of the eruptive events. The 1976 sequence of events is, in our estimation, typical of what one might expect during future eruptions of Augustine Volcano and we will therefore discuss this eruption in more detail.

Geophysical Precursors

The most promising geophysical parameters monitored on other active volcanoes for the purpose of eruption prediction are:

1) earthquake activity - spatial and temporal variations of source region and seismic energy release,
2) deformation measurements - changes in distance between benchmarks and tilt,
3) monitoring of mass (magma) movements under ground-changes in the gravitational field,
4) monitoring of magnetic and electric fields-changes in these fields are caused by changes of the thermal structure (Curie isotherm), by piezoelectric effects due to pressure changes and by mass movements of conductive fluids and gases,
5) changes in surface and fumarole temperatures
6) changes in gas flux and composition.

Prior to the 1976 eruption of Augustine we had principally concentrated on (l), (4) and (5) with the following results:

a) Even though we conducted detailed geophysical experiments on Augustine's summit from late June to August 1975 and spent a lot of time in view of the mountain and camped on the summit, we did not detect any obvious signs of the impending eruption only 5 months away, except for several felt earthquakes. This was unusual as we never felt any earthquakes during the prior field seasons (1970-1974).

b) Instrumentally detected precursor earthquakes to the January 1976 eruptions were observed over a period of 8 months starting in May 1975. The events were located centrally within the volcano at depths ranging from -6 to +1 km (datum is mean sea level) but most of them occurred at depth of -1 to +1 km (Lana and Kienle, 1978; Kienle et al., 1979; Lana, 1980; Lana and Kienle, 1980).

c) Two infrared radiometer surveys of the southwest face of the 1964 summit lava dome showed no change in temperature between 1974 and 1975. Snow melt pattern also stayed the same confirming this result. There was no change of heat flux between 1974 and " 975 of the hottest region on the top of the 1964 dome and all fumarole and shallow soil temperatures measured over the surface of the dome and in a fumarole field near its base were in both years below the local boiling point of 95°C (Lana and Kienle, 1976; Kienle et al., 1979).

d) No changes were detected in the gross magnetization of the volcano between 1972 and September 1975 that would have indicated demagnetization due to heating. However, one should keep in mind that this observation is based on comparing aeromagnetic surveys, which cannot resolve more subtle changes in the magnetization of the volcano (Barrett, 1978; Barrett et al., 1978; Kienle et al., 1979).

e) A seismic refraction survey using explosive sources failed to locate any large (>500 m) magma body at shallow depth (<1 km) beneath the volcano (Pearson, 1977; Pearson and Kienle, 1978; Kienle et al., 1979).

f) Repeated geodetic surveys since 1970 revealed no substantial (>30cm) growth of either the 1935 tholoid or the. 1964 dome relative to stable reference points on the crater rim (Stone, personal communication).

In summary, the only clear precursor to the 1976 eruption was a definite increase of seismicity in the 8 months prior to the January 1976 eruptions. We judged an intense earthquake swarm on November 18 and 19, 1975 severe enough to send a reconnaissance plane to the island and to announce the event in the Homer press but the photos taken revealed no visible changes at the volcano.

Vent Clearing Phase

This phase of the eruptions was the subject of a detailed paper by Kienle and Shaw (1979). Figure 13 (taken from Kienle and Shaw, 1979) summarizes the major events of this cycle. Two preliminary explosions occurred on January 22, 1976, at 7:59 AST and in the early afternoon The latter explosion cloud reached a height of 14 km as measured by a radar station in King Salmon (Lt. Col. Hanson, personal communication). Ash fell for the first time that evening at Iliamna, 90 km to the east-northeast.

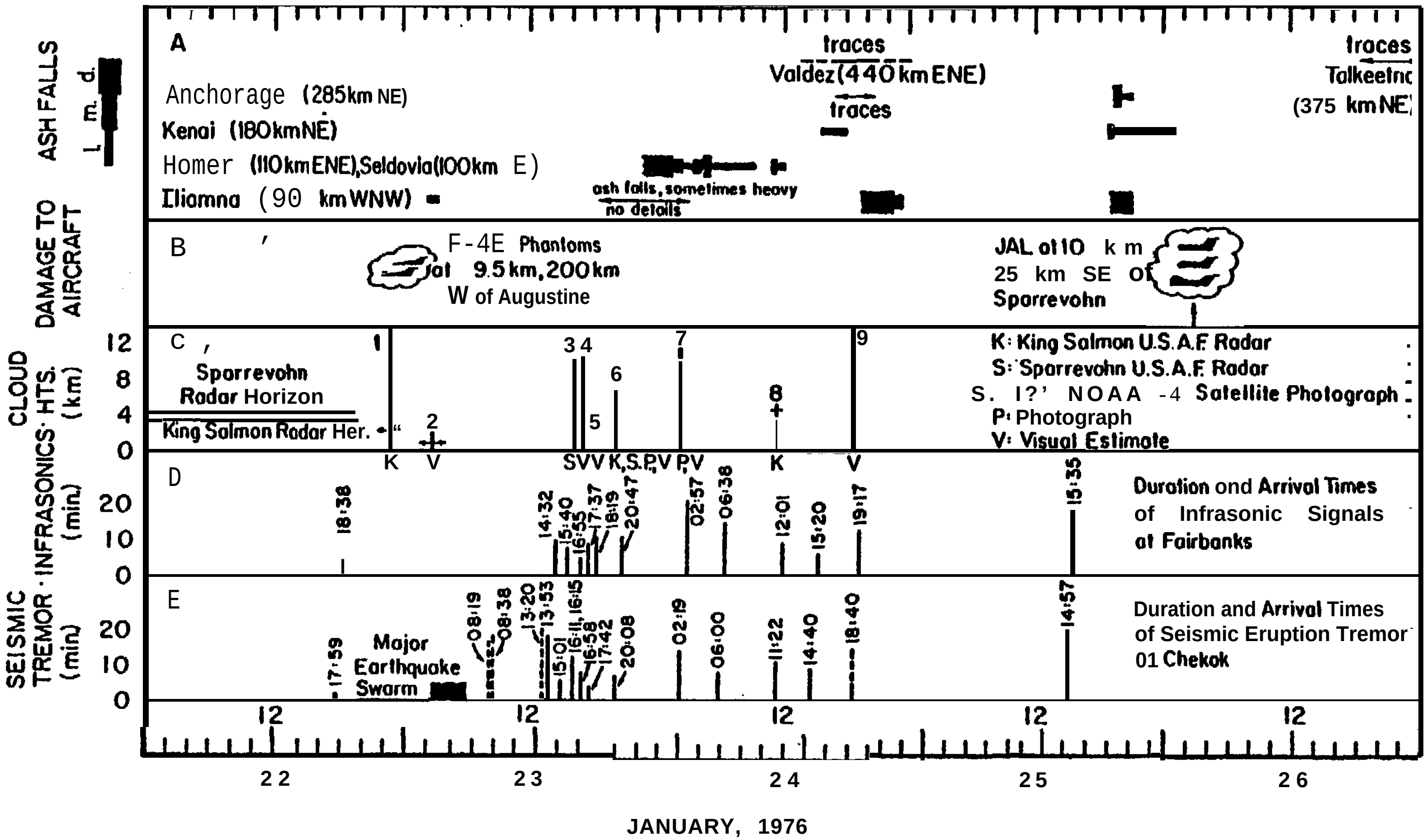
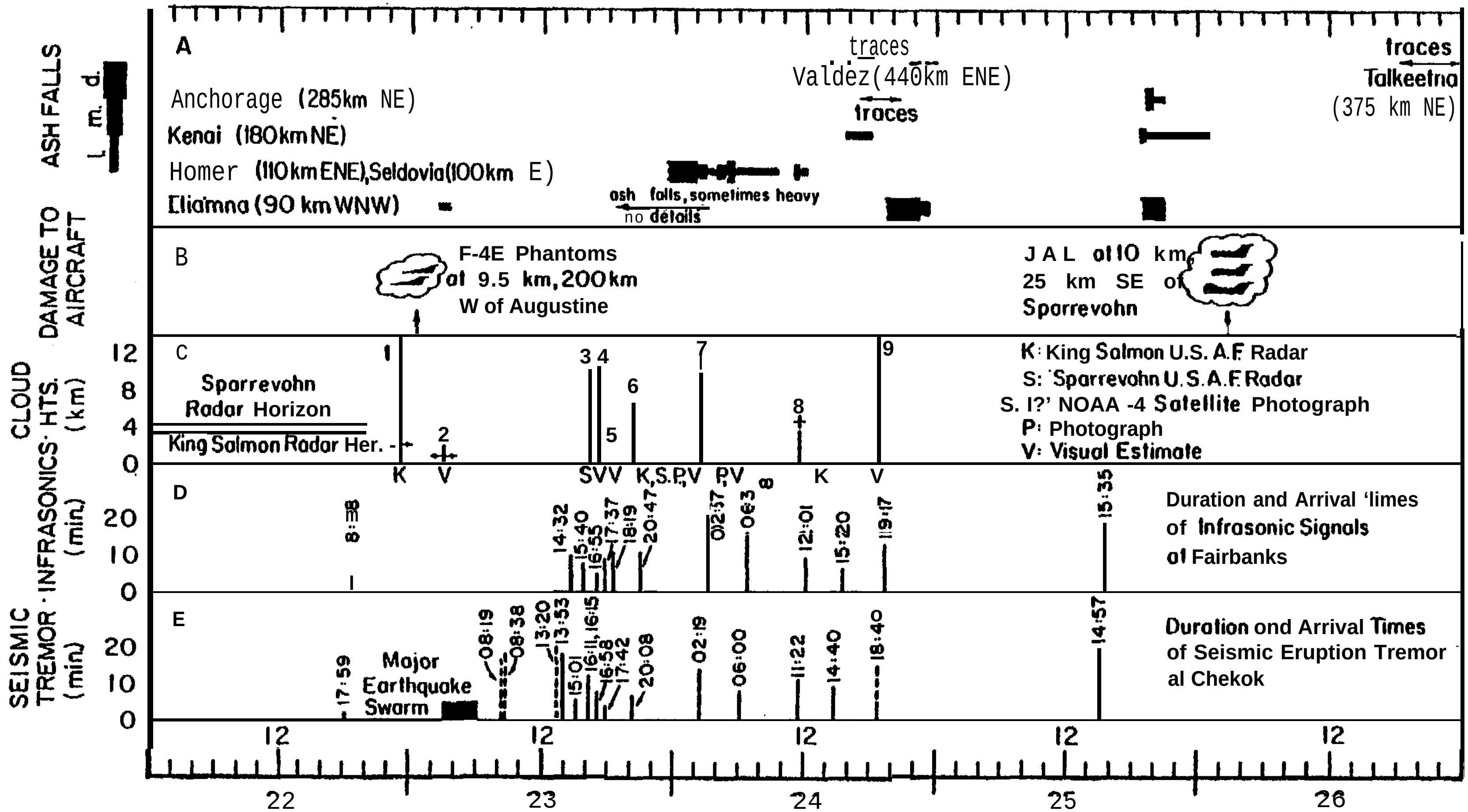


Figure 13. Summary of observations during the vent clearing eruptions of January 22-25, 1976, all times in U.T. A. Ash falls at various Cook Inlet localities based on surface weather log entries. B. Damage to aircraft. C. Cloud heights, numbers 1 through 8 refer to the source of information: 1 - Center for Short-Lived Phenomena (CSLP) event card 2367 and Observations by Lt. Col. Hanson, King Salmon Radar, exact timing is not known; 2 = Iliamna Lodge residents, exact timing is not known; 3 = Sparrevohn radar; 4,5 = Federal Aviation Administration (FM), Iliamna, M. Smith observed lightning; 6 = King Salmon and Sparrevohn radars, NOAA-4 satellite photograph indicates minimum height of 6 km, bush pilot reports a much higher (12 km) column near that time; 7 = photograph shown in Figure 16, eruption was heard 58 km north of the volcano by Chinitna Bay residents W. Byers and E. Hensley, who described the noise as a long roar, lasting a few minutes and sounding like "a gas jet at an oil well"; 8 = King Salmon radar; g = CSLP event cards 2367 and 2368. D,E. Arrival times and durations of infrasonic signals at Fairbanks and seismic eruption tremor at Chekok, 80 km northwest of Augustine, dashed lines indicate more questionable eruptions.

According to Lana and Kienle (1978), an important intense earthquake swarm originating centrally within the volcanic cone near and above sea level occurred in the late afternoon of January 22: Many events were large enough (M_L = 2.5-3.2) to be seen on seismic stations throughout the lower Cook Inlet region (up to 150 km away). This 3 hour long earthquake swarm released two orders of magnitude more seismic energy (5 x 10^9J) than had been released during either November or December, the most active months of precursor seismicity. The swarm probably signaled the breaking up of the rock column above a shallow (probably <3km deep) magma chamber.

Ten hours later, the main sequence of vent clearing eruptions began, resulting in the destruction of the 1964 summit dome and blasting out a crater 200 m deep (as determined by a radar altimeter), 600-700 m in diameter and breached to the north (Zoner, personal communication - he overflew the volcano after the January vent c"learing eruptions on a gas and ash sampling mission with NCAR personnel aboard an Electra aircraft).

From January 22 to 25, 1976, 13 major eruptions were detected seismically and infrasonically in Fairbanks (Wilson and Kienle, 1976) and there may have been others. Some of the eruptive plumes were observed by local residents of Lower Cook Inlet communities, were seen on U.S. Air Force radars and were photographed by the NOAA-4 satellite. Frequent lightning was sighted in the clouds (Figure 14). Of the 13 eruption clouds of late January several may have penetrated the tropopause, at about 10 km at the time of the eruptions. Ash was deposited over the entire Lower Cook Inlet region, over the Kenai Peninsula, reaching as far north as Anchorage, Talkeetna (375 km north) Cordova and



JANUARY, 1976

Figure 13. Summary of observations during the vent clearing eruptions of January 22-25, 1976, all times in U.T. A. Ash falls at various Cook Inlet localities based on surface weather log entries. B. Damage to aircraft. C. Cloud heights, numbers 1 through 8 refer to the source of information: 1 - Center for Short-Lived Phenomena (CSLP) event card 2367 and observations by Lt. Col. Hanson, King Salmon Radar, exact timing is not known; 2 = Iliamna Lodge residents, exact timing is not known; 3 = Sparrevohn radar; 4,5 = Federal Aviation Administration (FM), Iliamna, M. Smith observed lightning; 6 = King Salmon and Sparrevohn radars, NOAA-4 satellite photograph indicates minimum height of 6 km, bush pilot reports a much higher (12 km) column near that time; 7 = photograph shown in Figure 16, eruption was heard 58 km north of the volcano by Chinitna Bay residents W. Byers and E. Hensley, who described the noise as a long roar, lasting a few minutes and sounding like "a gas jet at an oil well"; 8 = King Salmon radar; 9 = CSLP event cards 2367 and 2368. D,E. Arrival times and durations of infrasonic signals at Fairbanks and seismic eruption tremor at Chekok, 80 km northwest of Augustine, dashed lines indicate more questionable eruptions.

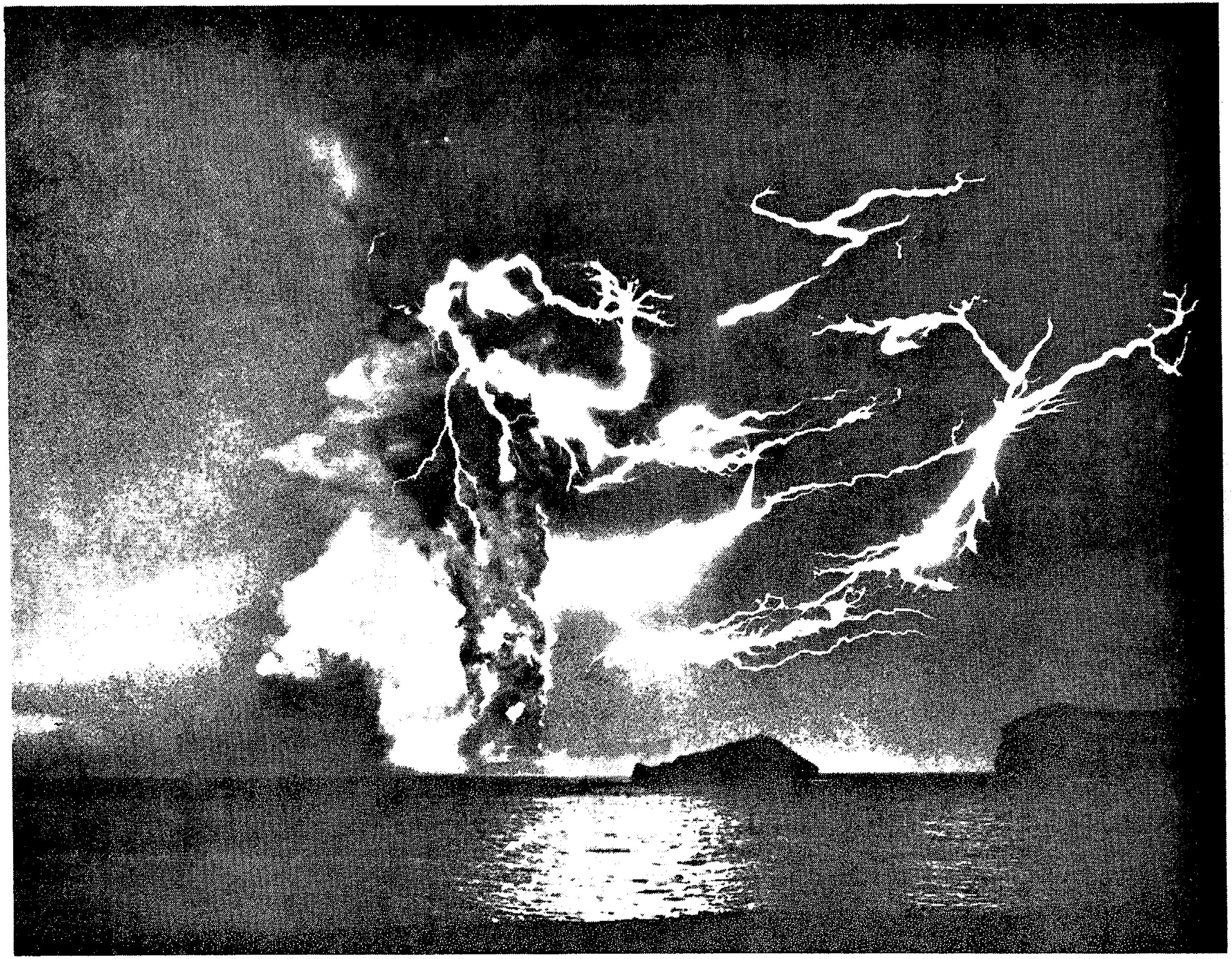


Figure 14. Lightning storm in eruption clouds of Surtsey Volcano, Iceland, December 1, 1963. Similar lightning has been reported for 1976 Augustine eruption clouds but we have no photo

Valdez, and over southeastern Alaska, where ash fell at Sitka, 1100 km distant (Figure 15).

A spectacular eruption occurred just before sunset on January 23, 1976, 16:19 AST. The anvil-shaped eruption cloud was photographed by one of us (J. Kienle) flying at 3,300 m altitude, 325 km northeast of the volcano (Figure 16). A low-lying cloud deck obscured visibility below 1,000 m. Photo-triangulation on the plume showed that most of it traveled below the 8-km level. A high-speed gas jet, directly over Augustine volcano reached a height of 11 km and penetrated the tropopause. The plume was spread out horizontally over 52 km by westerly winds when the photograph was taken. Figure 17 shows a sequence of frames of the same eruption seen head-on from the town of Homer, 110 km east-northeast and downwind from the volcano. Shortly after the last frame was taken, sand-sized (millimeters) ash particles began to fall out in Homer reducing visibility to a few hundred meters. Ash dispersal throughout this eruption was mainly governed by the high altitude winds. It is interesting to note that during several eruptions high altitude and surface winds dispersed the ash in opposite directions.

The ash dispersal of the January 22-25 eruptions was mainly to the north and east and rather limited to the West and south. Even though most communities in southern Alaska (from Talkeetna south), in Cook Inlet, the Kenai Peninsula and in Prince William Sound received ash, muddy rains or ashy snowfalls, no ash fell on King Salmon"or Kodiak throughout the eruptions.

The rapidly changing weather conditions between January 22 and 25 strongly affected the local ash dispersal. On the late afternoon of January 22 ash was carried to the west to the Iliamna Lake area {no

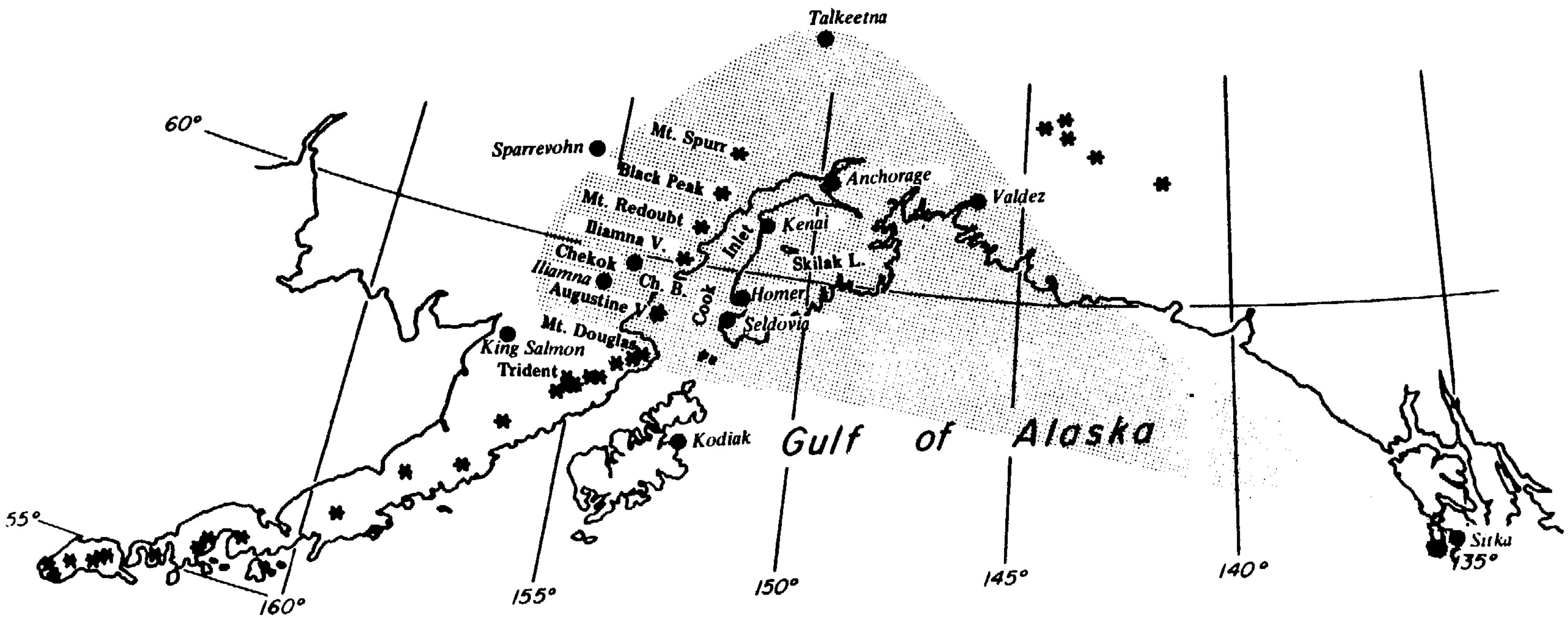


Figure 15. Area of ash fallout from 1976 Augustine eruptions.

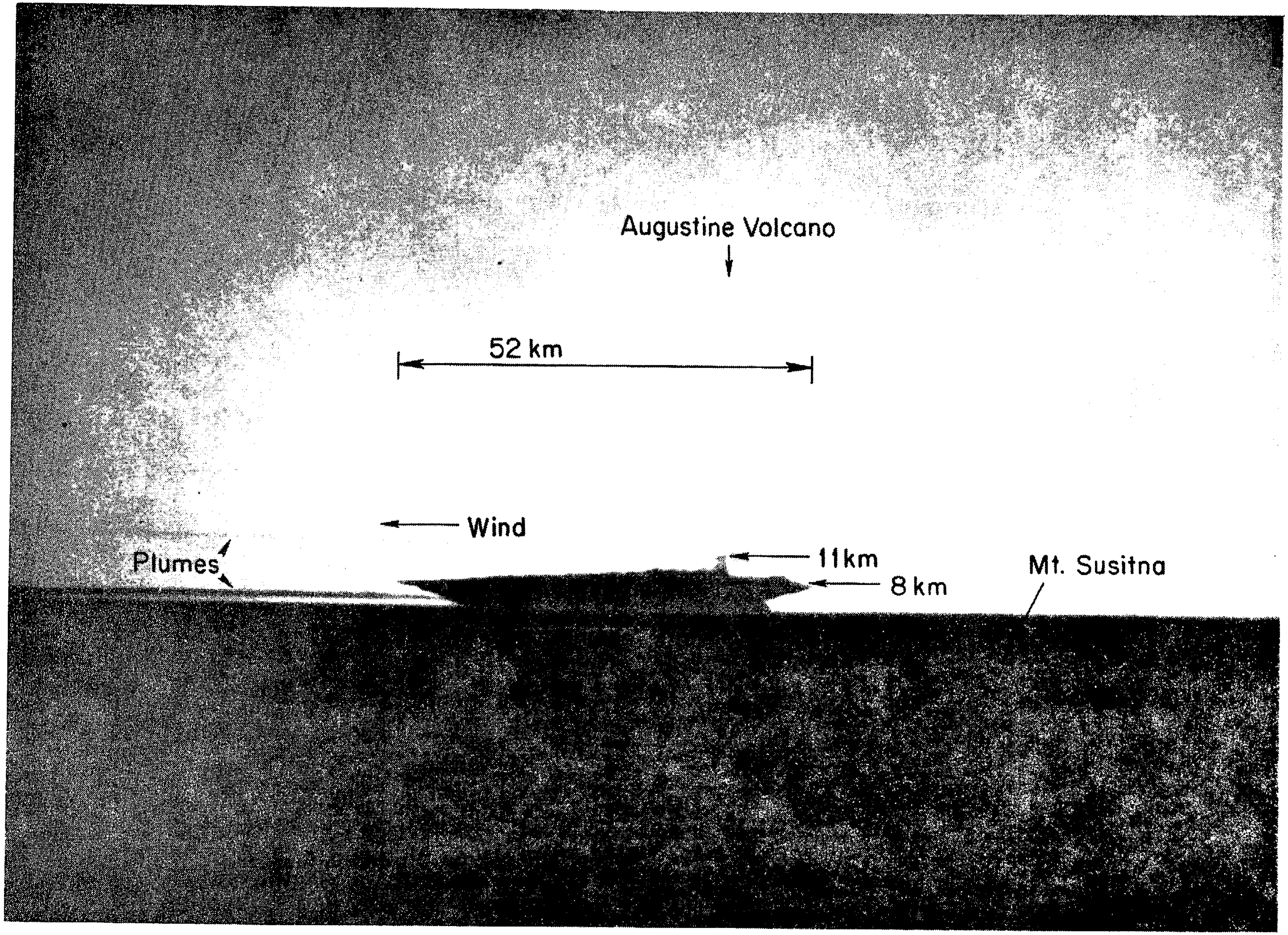


Figure 16. January 23, 1976, 16:19 AST, eruption seen against the twilight sky from aboard a Cessna 180 light plane flying at 3,300 m altitude, 325 km northeast of the volcano near Talkeetna. A gas jet marks the position of the volcano.

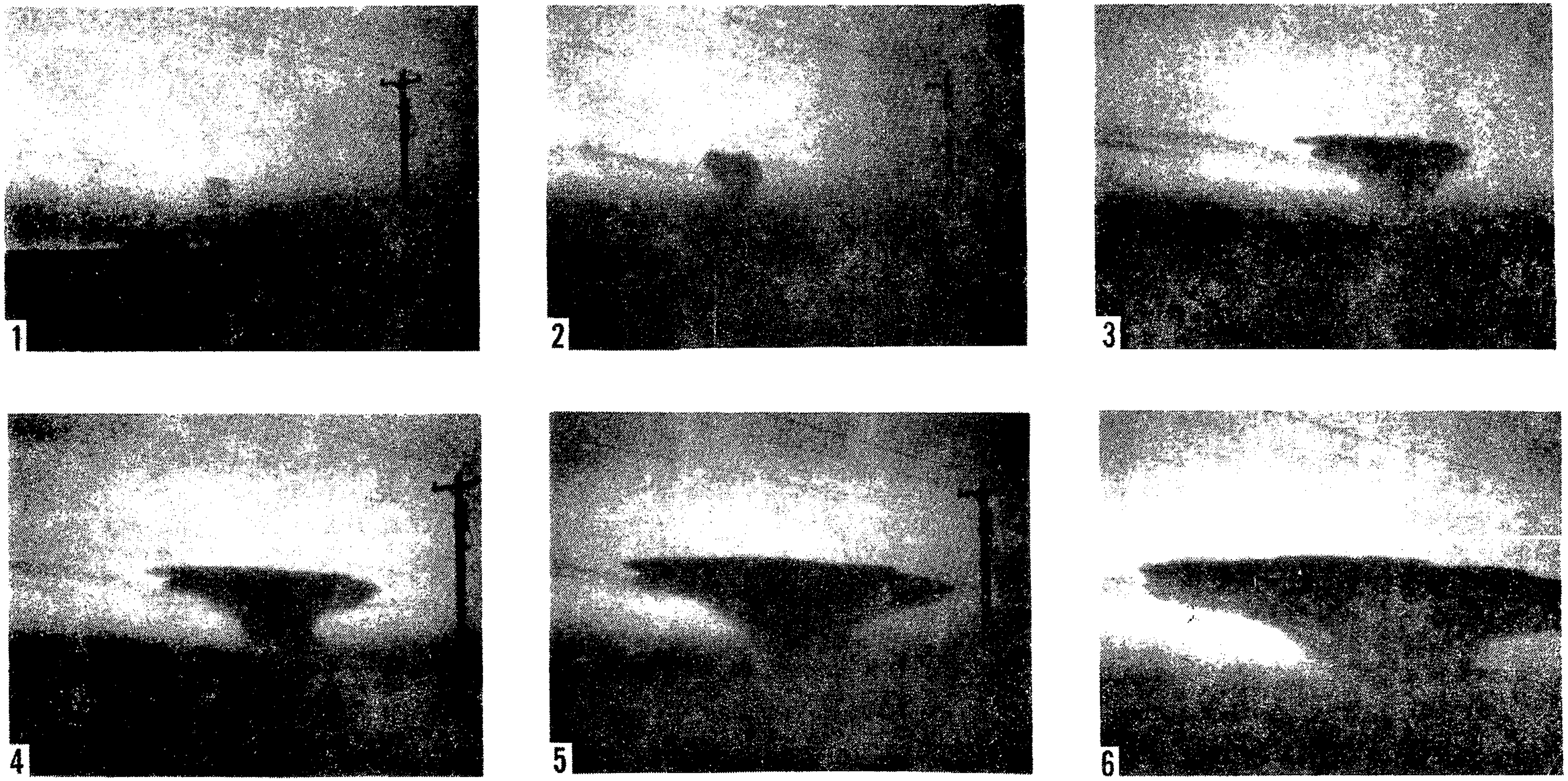


Figure 17. Same eruption as in Figure 16 seen head-on from Homer spit, 110 km east-northeast and downwind from Augustine Volcano. Photographs 16:20 to 16:45 AST by W. G. Feetham.

infrasonically or seismically detected event correlates with this ash fall, but Lt. Col. Hanson observed a huge, 14 km tall, 70 km diameter plume over Augustine on the King Salmon radar on the early afternoon which may have been the eruption that later caused the ash fall at Iliamna). ANOAA-4 satellite photograph taken on January 23, 10:10 AST, shows a string of high altitude eruption clouds from explosions at 3:53, 5:01, 6:11, 6:58, 7:52and 10:10 AST being dispersed to the east by60 knot winds blowing atan altitude of 6-8 km. An eruption was actually in progress when the picture was taken (Figure 18). In spite of this high altitude westerly flow, the 6:58 or 7:52 eruptions, or both, produced a dense ash fall at Iliamna 90 km to the west of the volcano reducing the visibility on the runway to less than 30 m, implying that easterly surface winds may have carried the ash that far to the west. During the daylight hours of January 23, a high pressure ridge developed over the Alaska Peninsula which resulted in a strong westerly flow over Lower Cook Inlet at 6 to 8 km altitude, where most of the ash traveled. As mentioned above, the spectacular 16:19 eruption shown in Figures 16 and" 17 spread eastward over the lower Kenai Peninsula, namely Homer and Seldovia, where 185 g of sand-sized ash was deposited in a 1 m^2 sampling area in 1 hour as the cloud passed overhead. Ash from this eruption eventually reached Sitka during the night of January 23. Between January 24 and 25 upper level winds generally blew more from the southwest dispersing the ash toward the upper Kenai Peninsula resulting in trace amounts of ash falling as far north as Anchorage, Talkeetna, Cordova and Valdez. Major eruptions occurred on January 23, 20:00, January 24, 1:22, 4:40 and 8:40 and January 25, 4:57 AST.

In Anchorage, fine ash mixed with snow fell in the very early morning hours on Saturday, January 24, and on Sunday morning, January

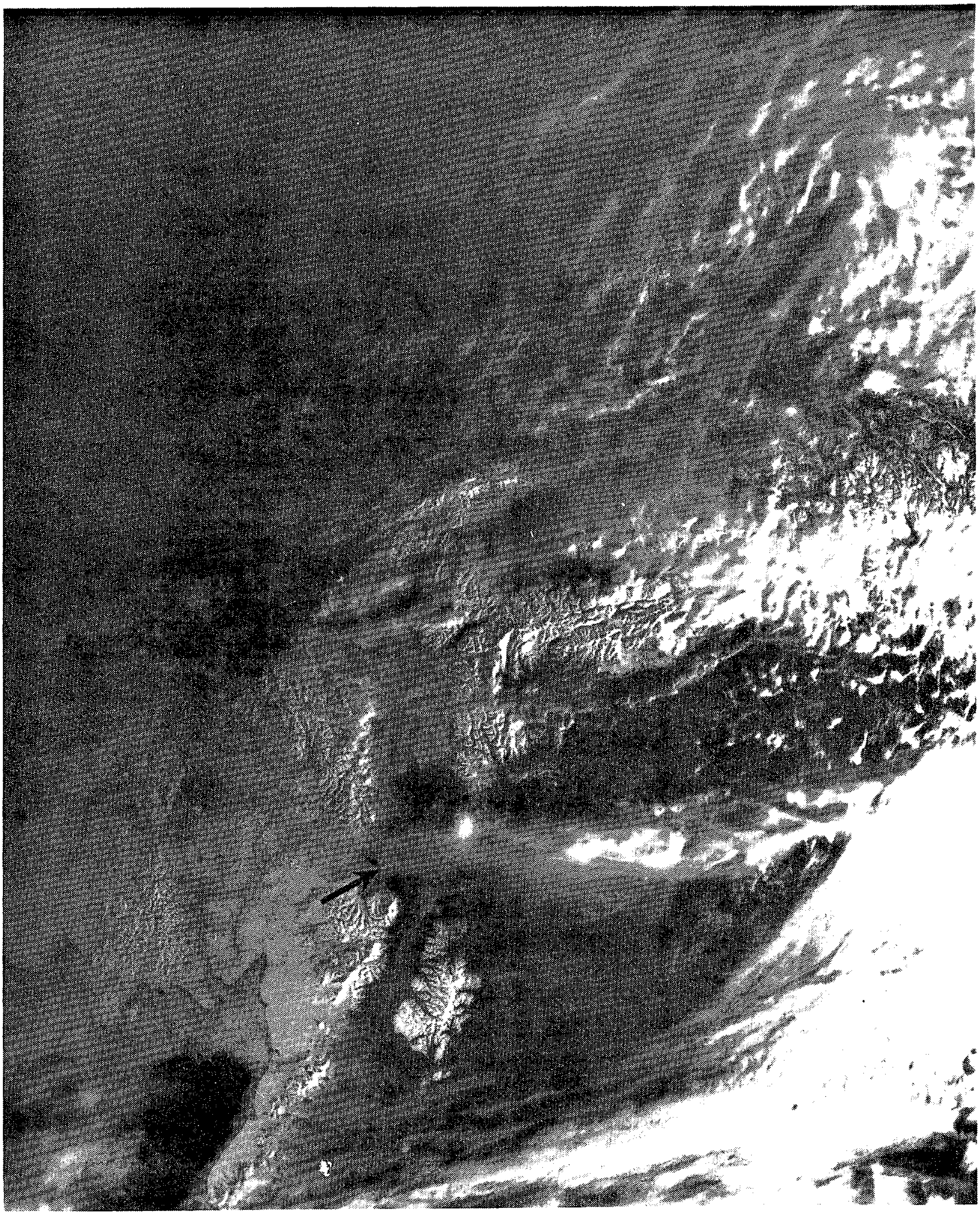


Figure 18. NOAA-4 satellite photograph of southern Alaska, January 23, 1976, 10:10 AST, in the visible (0.6 - 0.7 μm), showing eruption plume being dispersed across the Gulf of Alaska. An eruption is in progress and the 5.8 km high eruption column casts a shadow (arrow).

25, another large black cloud associated with the 4:57 AST eruption reached the city at about 9 a.m., reducing the visibility from 30 to 4 km! Miller (1976) reported that only 0.5 mm of brown ash accumulated, consisting of sharp angular fragments less than 0.1 mm across, but that was enough to irritate eyes of people wearing contact lenses, ruin the cross country skiing and scour layers of corrosion off the blades of natural-gas-powered turbines, actually increasing the efficiency of the machines.

Effects on Augustine Island

The following account of eruption-related effects on Augustine Island is principally taken from a paper by Kienle and Forbes (1976):

When a field party helicoptered to the island on January 29 during a break in activity following the vent clearing set of powerful eruptions, the island was thickly mantled by ash, and pyroclastic flows, probably formed by eruption column collapse (Johnston, 1978; Sparks et al., 1978). These deposits were noted on most flanks of the volcano, but occurred predominantly on the lower northeast slope (east of Burr Point). The flows in this northeast sector had reached the sea, forming an area of 0.1 km^2 of new land along a stretch of beach 3 km long. A fumarole field was actively degassing on the distal end of one of the pyroclastic flows where the hot ejects had impacted on water-saturated beach sands (Figures 19a and b). Temperatures greater than 400°C were measured 2.7 m below the surface of the upper pyroclastic flow unit east of the research station.

During that first visit we found that a small hut which had been built on the northeast flank of the volcano in earlier years of the project (Figure 20) had been severely damaged by one or more nuées

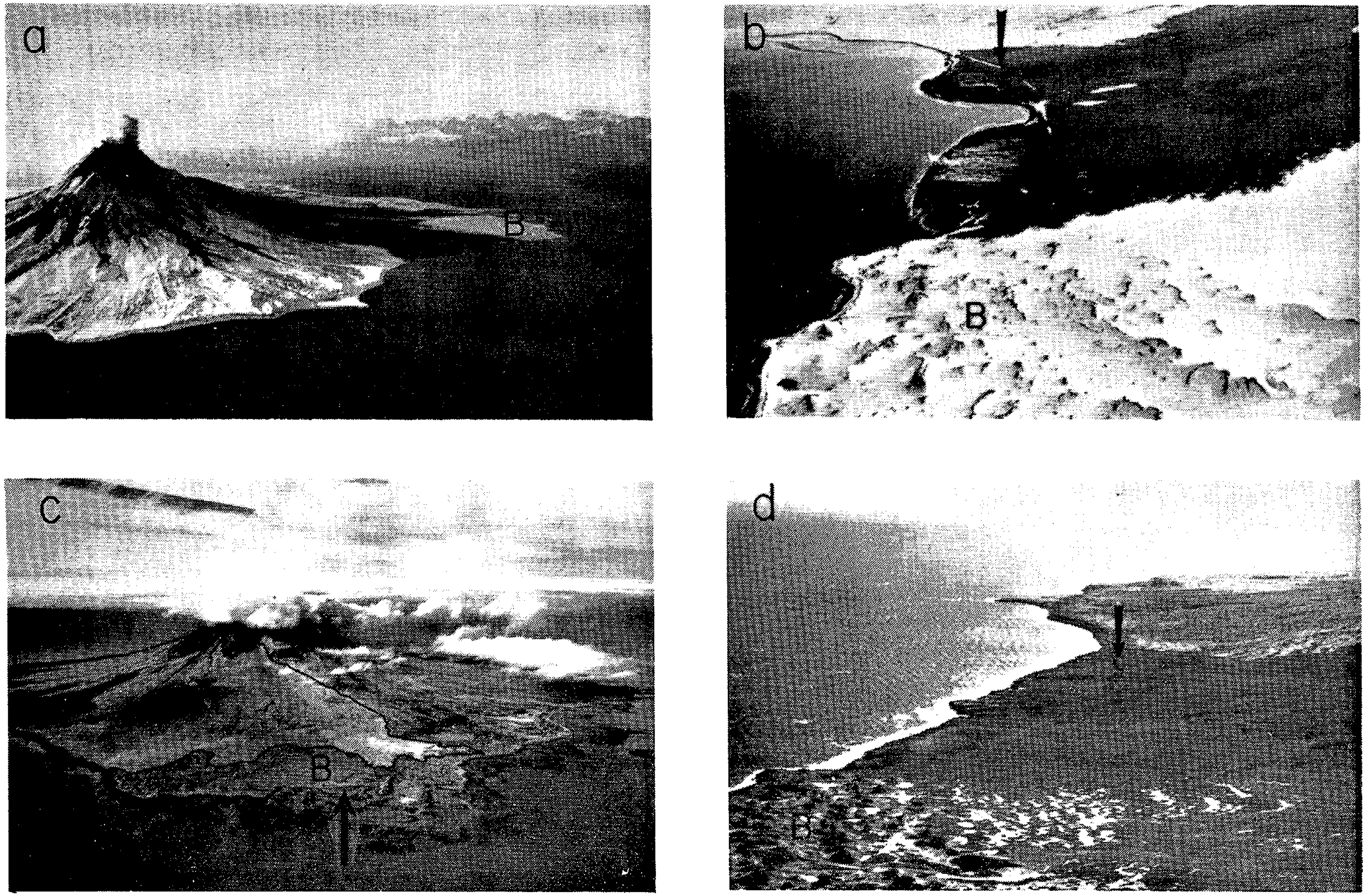


Figure 19. (a) Augustine from the east, February 1, 1976, showing new pyroclastic flow deposits on the northeast beach. (b) Close-up of the pyroclastic flow deposits, looking east, February 1, 1976; arrow points to old beach line, B marks Burr Point. Note steam rising from the deposit seaward of the old beach line. (c) Augustine from the north, June 13, 1976, showing distribution of pyroclastic flow deposits, arrow marks Burr Point cabin site. (d) Same beach as in (b) on February 27, 1976; the early February pyroclastic flow eruptions have altered the beach line significantly. Photographs a, b and c by

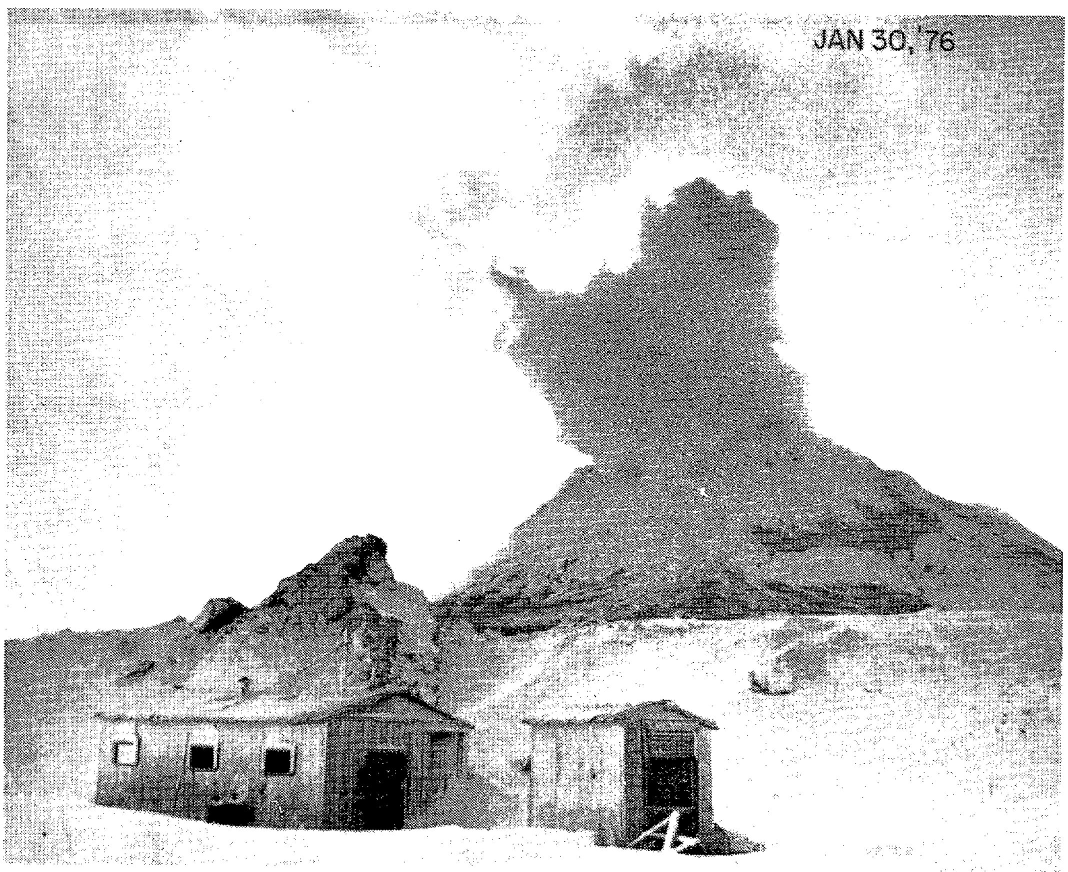


Figure 20. Burr Point Camp before and after passage of a glowing cloud (nuee ardente). Note mountainward dent in smaller generator building, produced by back-eddy effect when the nuee passed over the small ridge protecting the camp.

ardentes (glowing clouds). The main research station at Burr Point (see Figure 19c for location arrow), a corrugated aluminum building, had sustained major damage from air blast and thermal effects, accompanying nuée ardente eruptions (Figure 21), although relatively little ejects had fallen on the site (see Figure 19b for location of Burr Point - area B). The Burr Point location had been chosen for proximity to a sheltered harbor for resupply and access by sea. Additionally, the two corrugated aluminum buildings were sited on the lee side of a small hill for protection against possible blast effects - a provision which proved totally inadequate for the January nuée ardente activity. The site and the surrounding low hills were mantled by a relatively thin blanket of ash lapilli and small blocks of pumice and andesite, probably associated with the January 25 erruption. Residual clumps of charred grass projected through the ejects blanket, and driftwood along the beach was charred on the side toward the volcano though relatively undamaged *on* the opposite side (Figure 22). Drums of jet fuel cached at our helicopter pad were not ignited, although paint on the barrels was discolored. The helicopter pad was not in the lee of the hill, but the barrels were nearly covered with snow prior to the eruptiens. All of the windows were broken on the north side (seaward side) of the main building, which faced away from the volcano. The corrugated aluminum siding was also dented in from the same side. The siding was torn loose from the east end of the building and two mattresses were incinerated near the window opening. Mattresses in protected positions were not ignited. The roof had been pierced by falling ejects ranging in size from lapilli to small blocks. The floor was covered by about 5 centimeters of fine ash. A vertical 2" x 4" antenna support on the roof was charred on the side away from the volcano,

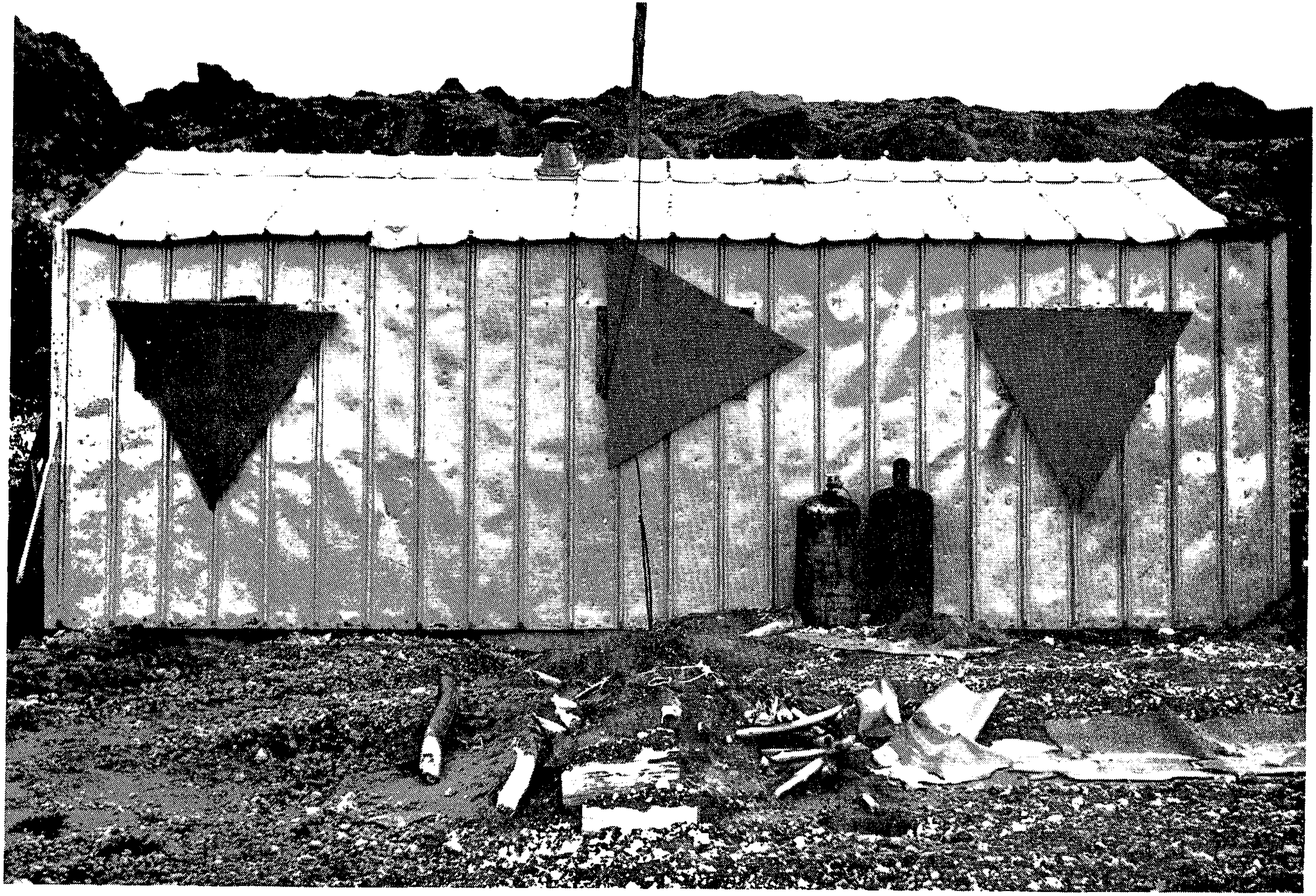


Figure 21. The main aluminum building at Burr Point dented and punctured by steep angle impact of lapilli from the side facing <u>away</u> from the volcano. All windows were sucked out by the Venturi effect of the passing hot cloud (photograph by H.-U. Schmincke, Ruhr-Universität Bochum, W-Germany).

Figure 22. Charred driftwood burned by passing nuée ardente at Burr Point (photograph by H.-U. Schmincke).

uncharred on the other side. Exterior covering on R-G4U coaxial cable leading to the support was also partially melted. A plastic towel holder located under the kitchen window sill showed the effects of partial fusion, and a plastic measuring cup on a shelf at window level was also partially melted (Figure 23). Some of the paper wrappings and cartons on these same shelves showed incipient charring. A battery which was sitting on the floor opposite a window also showed the effects of incipient melting.

Based on the damage discussed above, we conclude that the Burr Point camp was overrun by one or more nuées ardentes. Considering the relatively thin blanket of ejects and the similarity of the pumice and lithic fragments to that in the lower pyroclastic flow unit in the January series of deposits east of Burr Point, we deduce the following history:

(1) One or more major explosions were accompanied by nuées ardentes down the northeast slope of the volcano. At Burr Point, Johnston (1978) distinguished at least 3 fine ash layers beneath the coarse January 25 blanket of tephra that could have formed by nuée ardente activity.

(2) The research station was not in the direct path of the basal glowing avalanches, which turned east near the head of the Burr Point high terrain but was overrun by turbulent hot gas and dust clouds (nuée ardentes), which initially formed above the avalanche but then detached from the main flow and traveled straight over Burr Point and out to sea.

(3) The dust cloud flowed at high speed over the small hill mountainward of the buildings broke the windows probably by Venturi suction (the glass was laying outside!) and then formed a back eddy which dented the aluminum siding on the seaward side of the building (Figure 20, bottom).

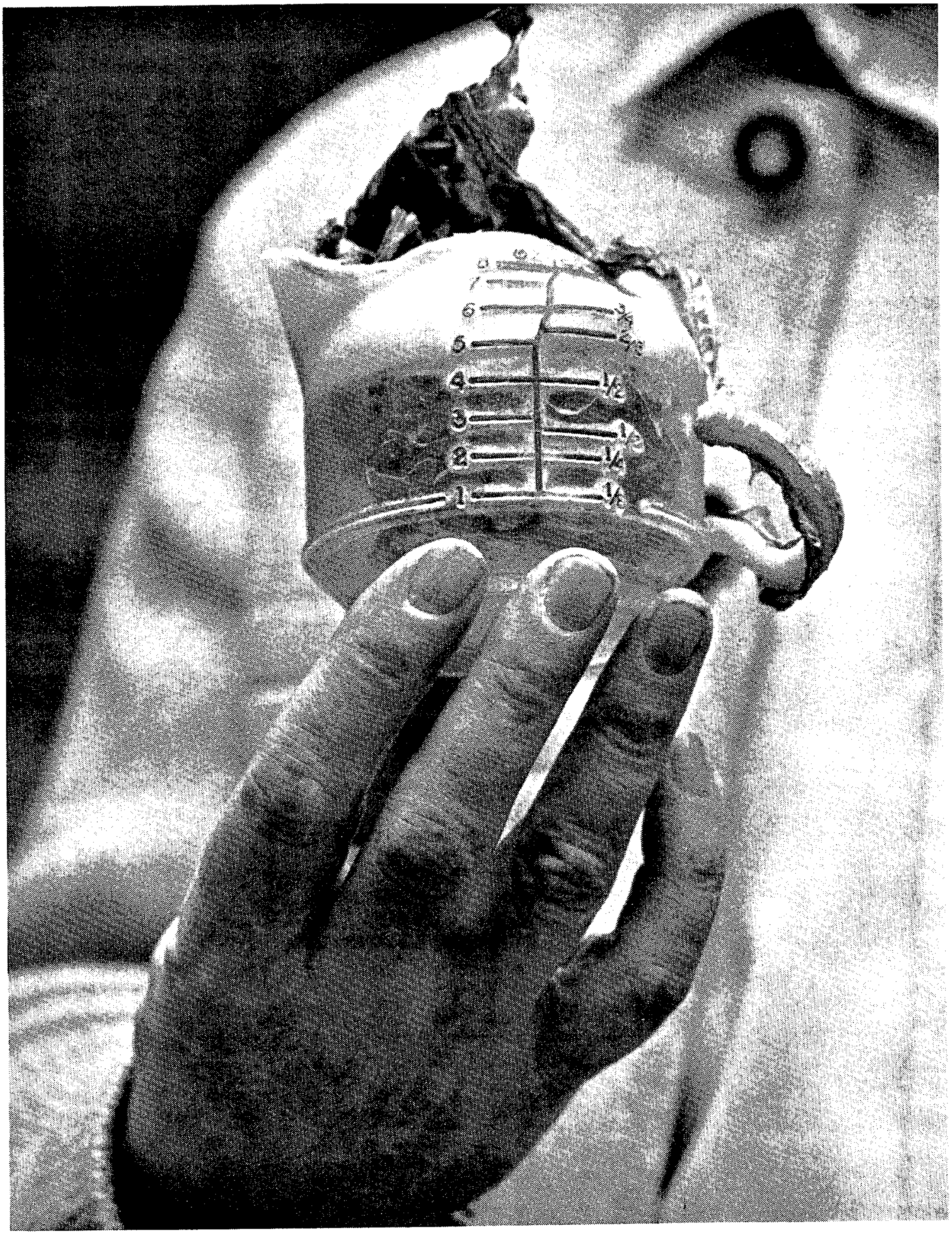


Figure 23. Partially melted plastic measuring cup recovered from inside the main building at Burr Point.

4) Gas and ash ofa hot dust cloud passing over the camp flowed through the window openings, igniting mattresses and partially melted low-temperature plastics.

(5) Perforations in the roof were made by small bombs (one was however 10 to 20 cm in diameter - at a distance of 6 km from the summit!).

(6) A rain of 1 spill i and smal l bombs thoroughly dented the aluminum by high angle impact from the seaward side of the building (Figure 21).

(7) Clearly, no resident would have survived the nuées ardentes that swept through the camp. We had located the station in defilade beh nd a ridge for shelter from possible blast effects, and we were also mis ed by the fact that the site was at a relatively long distance (6 km) from the vent as compared to other potential sites on the island. Nevertheless, the glowing clouds not only reached the site, but were probably lethal on the lee side of the ridge. The nuée(s) ardente(s) must have passed the station at great speed (order 50 m/see or 180 km/hr, as measured by Stithet al., (1977)) and their temperature was probably several 100 °C (300 to 700°C). Death to residents would have most likely occurred through inhalation of hot dust particles, burning the lung tissue as in St. Pierre in 1902 (Anderson and Flett, 1903).

In spite of this damage, the Burr Point cabin was a welcome bivouac shelter for a field crew of us, who were stranded at Augustine from February 2 to 5 because one of our helicopters had crashed due to an engine failure. During that time we were amazed to find island survivors of the eruption. Fox tracks crossed the new pyroclastic flows on the northeast sector and we saw a group of foxes at the small western island. Other wildlife was apparently not so lucky as we found the charred wing of a seagull laying atop the new pyroclastic flow deposits on the north-eastern flank of Augustine.

February-April eruptions

After 12 days of quiescence, explosive activity on Augustine was renewed at 04:43 AST on February 6, when muddy rain and ash was reported from Kenai and Soldotna on the Kenai Peninsula and the last infrasonic signal from the 1976 Augustine eruptive cycle was recorded in Fairbanks (all further eruptions were too weak to produce any more infrasonic signals that could be seen on the Fairbanks detection array). There is a suggestion that both the solid earth as well as the ocean tide may have triggered explosive activity (Kienle and Forbes, 1976). Major eruptions preferentially occurred near the peak (or maximum load) of the ocean tide as did the 04:43 February 6 eruption. On February 6 a pilot from Seldovia, Gary Gunkel, flew to the island and landed his Supercub on the beach on the west side of Augustine. Figure 24 is one of the spectacular eruption photographs he took on that day. Fresh mudflows (black) and lighter colored dry pumice and pyroclastic flows (overriding black mudflows) descended again nearly all flanks of the volcano, as can be seen from his view from the west. The eruption column had actually begun to collapse when the picture was taken and is feeding a dense nuée ardente which is descending the northeastern flank of the volcano. The same eruption was photographed shortly after noon by M. Tollefson from a commercial Wien Air Alaska airliner on its way from King Salmon to Anchorage (Figure 25). The eruption column rose to a height of about 5.5 km and a few hours later gave rise to a dense "blizzard-like" ash fall at Homer, reducing the visibility to about 1 km. This eruption is an example of an eruption that was too small to generate any seismic signal on mainland stations or generate an infrasonic signal.

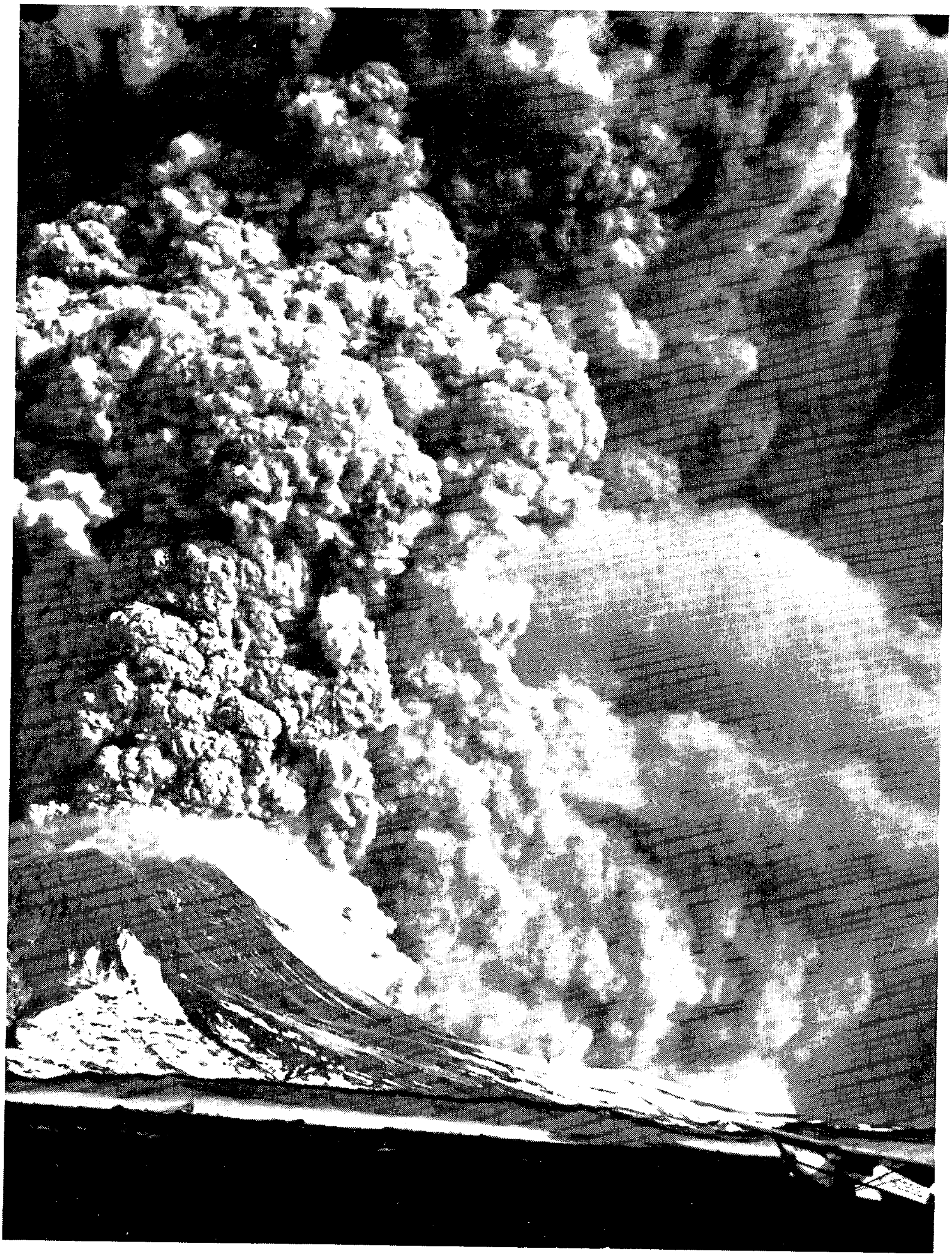


Figure 24. Augustine Volcano in eruption on February 6, 1976. A nuée ardente is descending the northeast side (Burr Point area) of the volcano. Fresh black mudflows have melted the snow in places (photography by G. Gunkel).

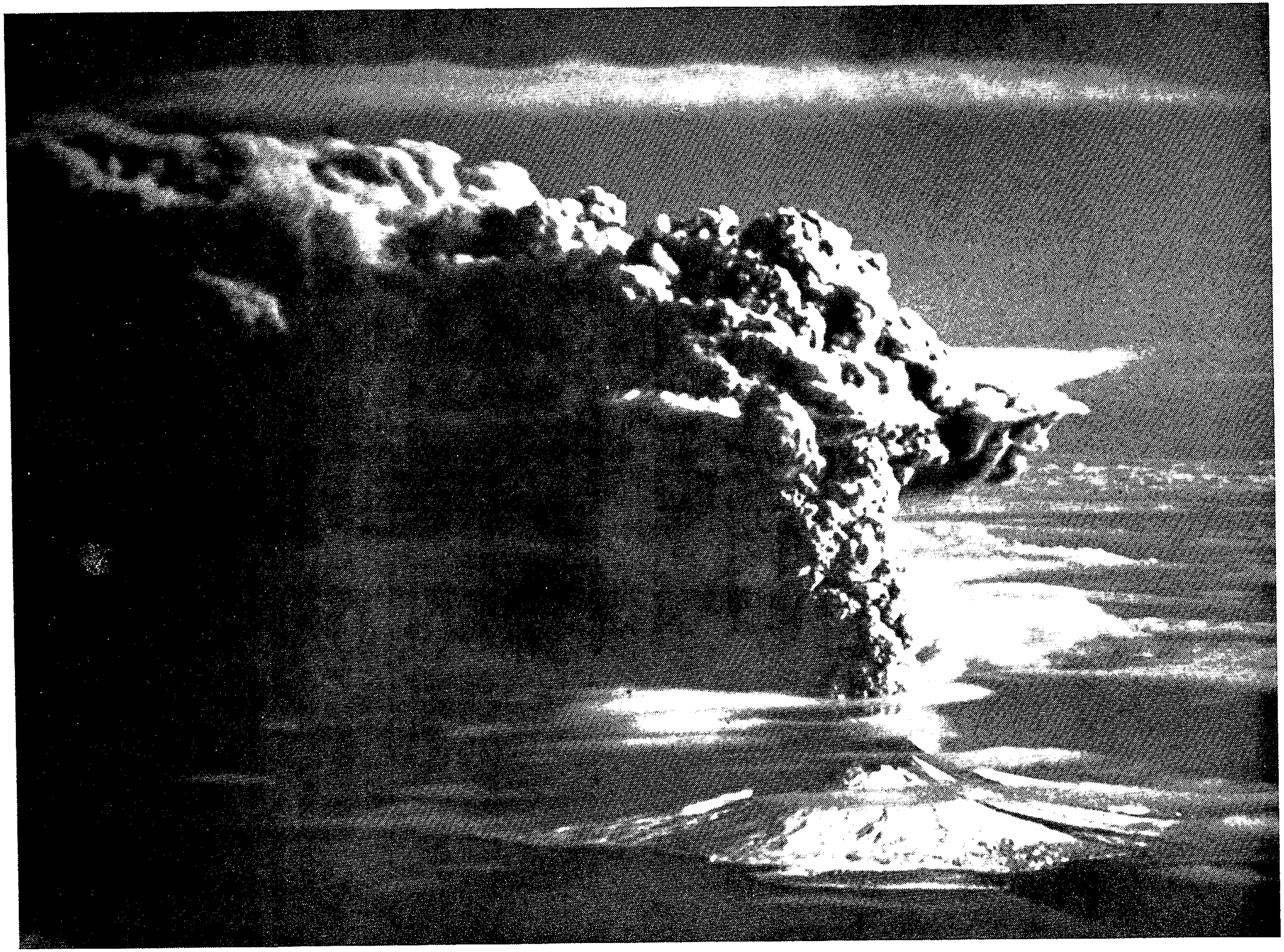


Figure 25. Same eruption as shown in Figure 24 photographed from aboard a commercial jet airplane. The eruption column is 5.5 km high. Shock wave phenomena can be seen in the atmosphere above the erupting volcano (photograph by) M.E. Tollefson, National Park Service)

Between February 6 and 15 a crew of cloud physicists flew frequent missions over the volcano with a special aircraft (modified B-23), equipped to sample gases and small particles. They witnessed several ash eruptions, one or more northward directed blasts and pyroclastic avalanches with associated nuées ardentes (Hobbs et al., 1977; Stith et al., 1977). Figure 26 shows one of these nuées ardentes on February 8, 14:00 AST, issuing from the northern notch in the new summit crater rim and descending the northeastern flank of the volcano. According to Stith et al. (1977) who photographed the cloud with a time lapse camera, the nuée rushed down the mountain at a speed of 50 m/see (180 km/hr) while on the upper steep (~1:3) slopes and then slowed to about 6 m/see (22 km/hr) near the base of the cone (slope ~1 :25). The total distance traveled by this small nuée was about 5 km. Strong winds of about 25 m/see (90 km/hr) caused the nuée to drift away from the basal pyroclastic avalanche. Stith et al. report that while most of the avalanche was still on the steep slope, a dense black cloud (nuée ardente) was billowing from it along its entire length. Later, the nuée overtook the toe of the slowing ground avalanche near the base of the volcano, while the rear portion of the pyroclastic avalanche was still speeding down the steeper inclines of the cone. Finally, a white plume rose from the place near shore where the avalanche had entered the sea. The volume of this particular avalanche was probably too small for it to continue beyond a few 100 m underwater.

The high mobility of these pyroclastic avalanches is caused by fluidization as the incandescent material within the flow autoexplodes releasing hot gases and fine particles (Sparks, 1976; Sparks and Wilson, 1976) and as air is entrained in the flow. The January pyroclastic

Figure 26. Nuée ardente (glowing cloud) descending toward Burr Point on February 8, 1976, 14:02 AST. The nuee reached a maximum speed of 50 ms^{-1} (photograph taken from article by Stith et al., 1977).

flows were so mobile that the avalanche producing the deposits seaward of the beach?"ine shown in Figure 19a actually jumped the original beach bluff leaving charred blades of grass still standing when we visited the island in late January. Evidence that January avalanches higher up on the volcano became airborne can be seen in Figure 27 top right (arrow), where black avalanche deposits on the right side of the summit suddenly end on top of a small bluff created by an old lava flow, and then continue far below it.

The frequency of eruptions declined from February 6 to about 16 per day. On the most active day, February 8, Reeder and Lahr (1976) reported about 10 exp"losion earthquakes, detected at a seismic station (CKK) 75 km northwest of the volcano. No more ashfalls were reported from the Kenai Peninsula after February 6/7.

By February 12, a new dome began to intrude the January crater (Figure 28) and associated with this intrusion pyroclastic flow activity changed from the eruption column collapse type (Soufriere) to the dome collapse type (Merapi) (see also Figure 29).

Schmincke and Johnston (1977) report that:

> "...early deposits (January 22-25, February 5∿8) are distributed radially about the island, contain abundant banded and unhanded pumices and accidental clasts, and have vesicular glass coatings on crystals, thin gradually to their margins, and are associated with extensive ash-cloud and air-fall deposits. Later deposits (February ∿8-18, mid-April) were emplaced below a breach in the crater wall only, are coarser grained, nearly monolithologic (dacite), have poorly vesicular shards and glass coats, lack pumices but contain expanded bombs to 10 meter diameter, and terminate in steep lobate flow fronts.
>
> Early pyroclastic flows probably formed by collapse of an eruption column. Abundant ash formed in the eruption column and from the flows. Decrease in gas content and/or crater widening may have lead to the gradually decreasing areal extent of the flows. Later flows appear to have formed by collapse of a dome, which first appeared in the crater [around] February 10. Little ash was produced during these eruptions ..."

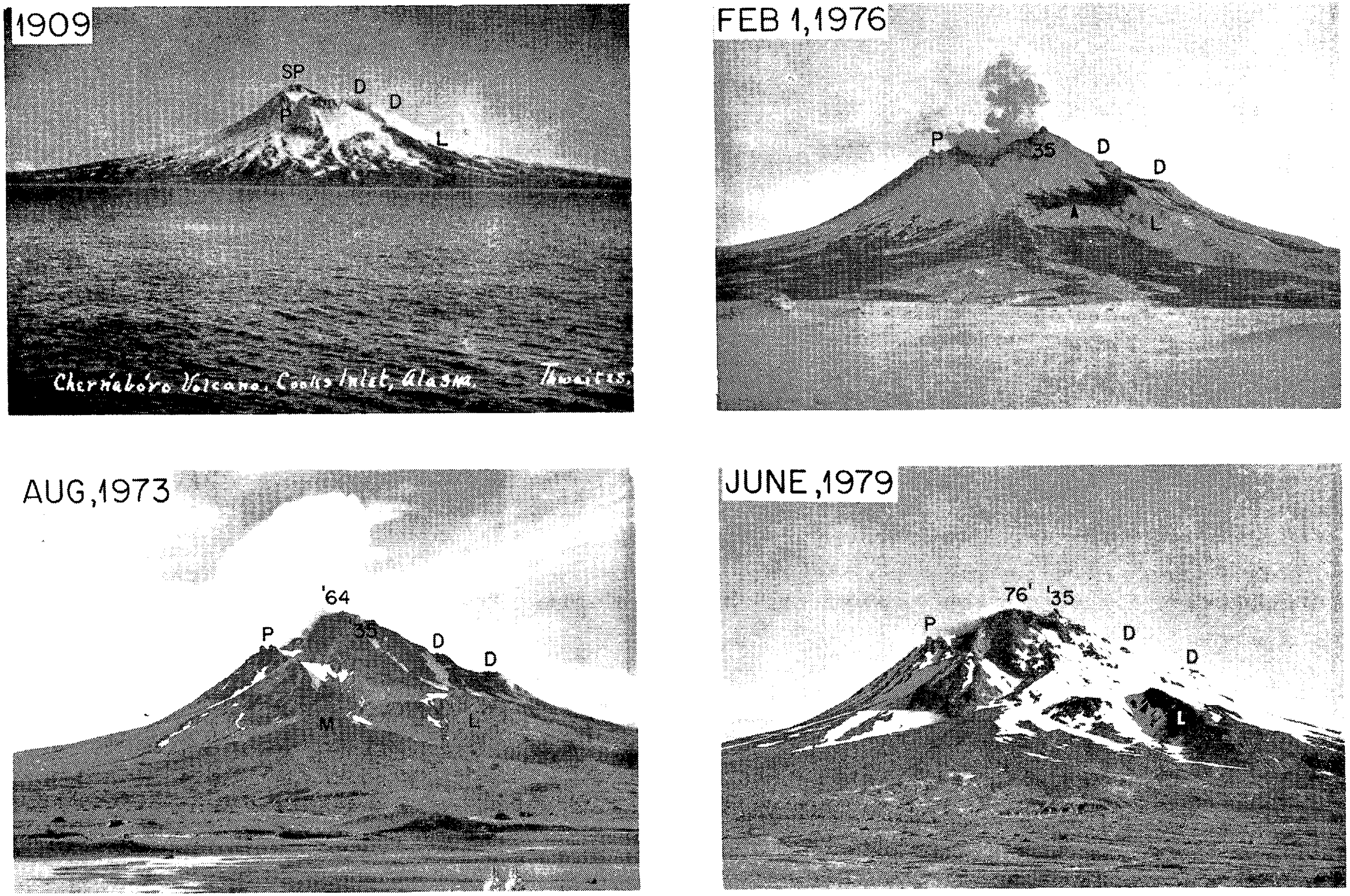


Figure 27. Series of historic photographs from the north, showing the evolution of Augustine Volcano. Reference points for comparison are P = pair of pinnacles, D = two prehistoric lava domes, and L = lava flow. SP is the former South Peak, engulfed later by the 1963-64 lava dome. M is a mudflow erupted in 1963-64. The 1935, 1964 and 1976 lava domes are marked. Chernaboro (1909 picture) is a local corruption of the Russian name (Ostrov) Chernoburoy, meaning "black-brown" (island) (Orth , 1967). The Feb. 1, 1976 picture shows the new crater formed in January; the fresh pyroclastic flows contrast black against the snow, arrow marks the place where one flow jumped a cliff-forming old lava flow.

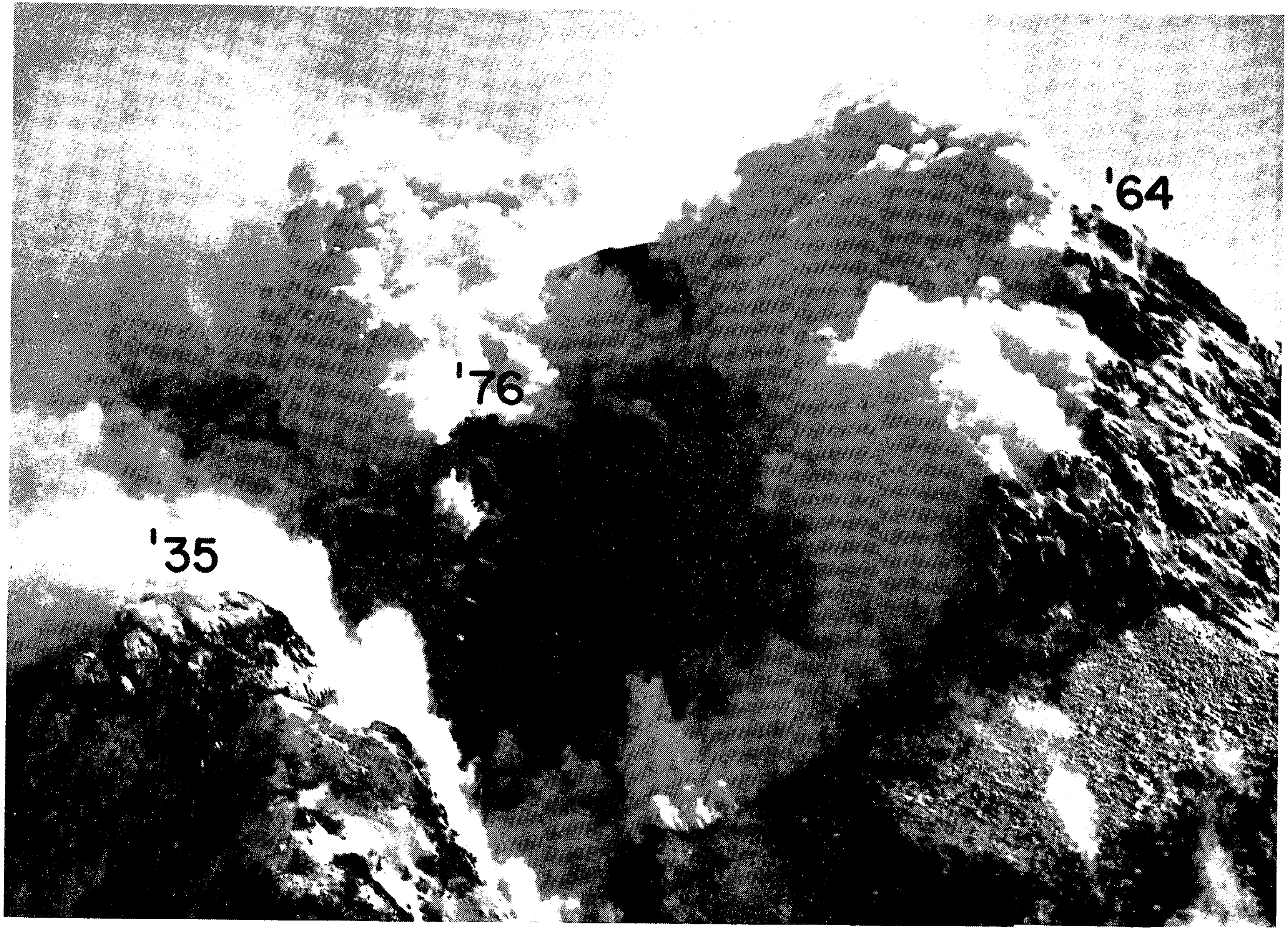


Figure 28. Close-up of the 1976 lava dome; 1935 dome remained unchanged; most of the 1964 dome has been removed during the January explosions.

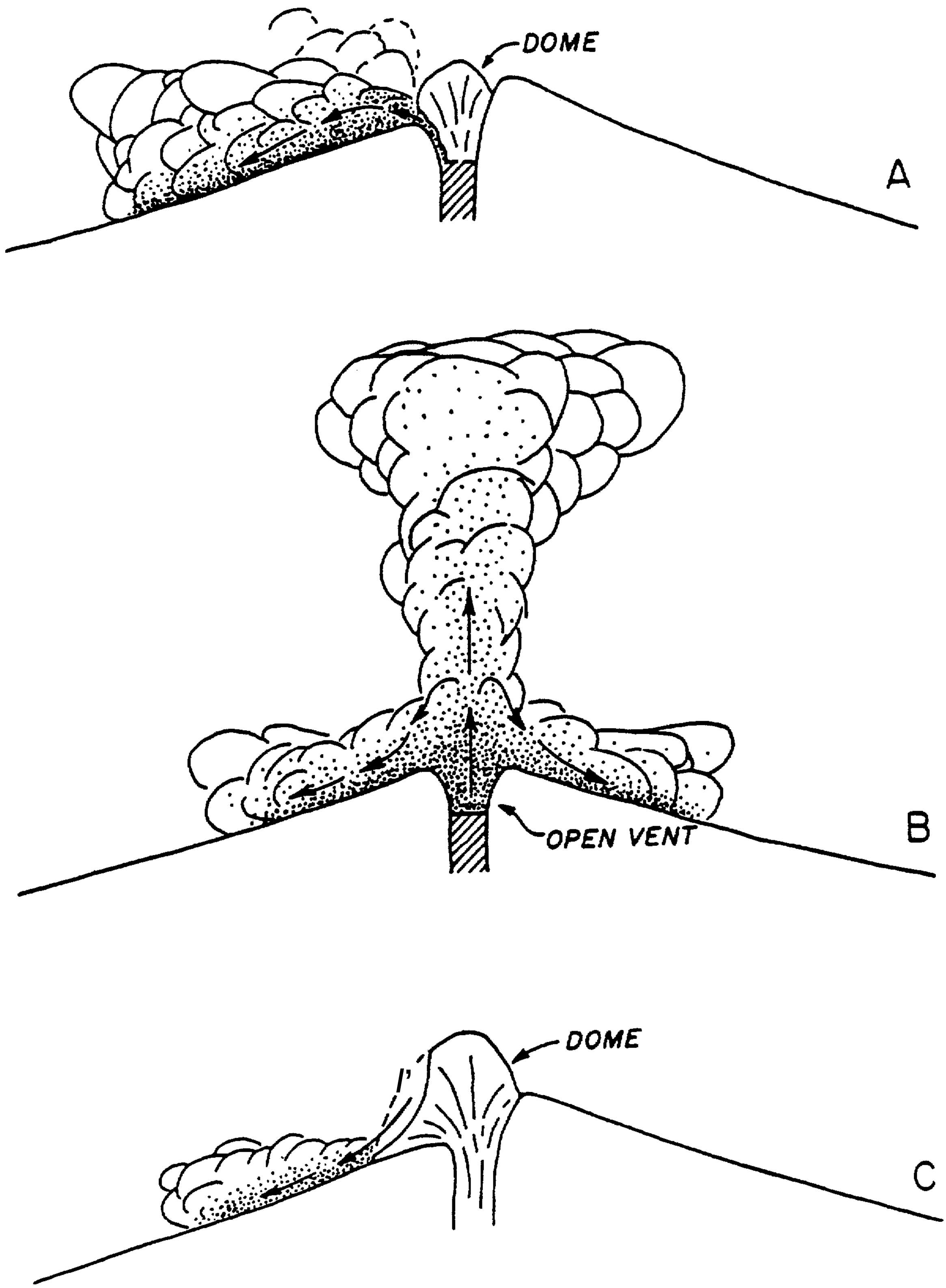


Figure 29, Types of glowing (pyroclastic) avalanches and associated nuées ardentes: (A) Pelee type (directed blast); (B) Soufriere type (column collapse); (C) Merapi type (dome collapses taken from MacDonald, 1972, p. 149).

A University of Alaska team visited the volcano again during the period February 18-28. Although the Burr Point station had sustained no further damage, many additional pyroclastic flows of the Merapi type had been deposited along the same general path as the earlier flows. Strong fumarolic activity extended at least 2 km upslope from the beach line. Temperatures of 600°C at a depth of 5 meters were measured at a location several hundred meters up from the beach (Figure 30). The main heat source of the deposit were large juvenile blocks of the new lava dome that were entrained in the debris flow. By September 26, 1976 the bottom hole temperature had dropped to 434*C and a year later on August 2, 1977 it had cooled to 76°C, i.e. below the boiling point.

"All flow deposits were emplaced at high temperatures (>600°C), are coarse-grained (Md>2mm), have small areal extent (<5 km^2) and volume (0.001 km^3), and contain abundant lapilli (degassing) pipes." (Schmincke and Johnston, 1977). The total volume of the 1976 pyroclastic flow' deposits in the northeast sector of the volcano (Figure. 31) was determined by digitizing the pre and post-eruption topography and is 0.05 km^3. A similar computation for the volume of the 1964 pyroclastic flows and mudflows in the same sector yields a volume of 0.024 km^3.

Figure 32 is a photograph by H.-U. Schmincke showing the fan of avalanches that developed on the north side beneath the collapsing new dome which was vigorously steaming in the summer of 1976. Figure 33 is a close-up of the notch carved by the February pyroclastic flows - the brightly colored area (due to active sulfur deposition) in Figure 32 at the base of the new dome. At that location the January/February dome avalanches actually eroded out a gorge in the older debris flow deposits (notice people for scale) which was again partially buried by debris from the April avalanches.

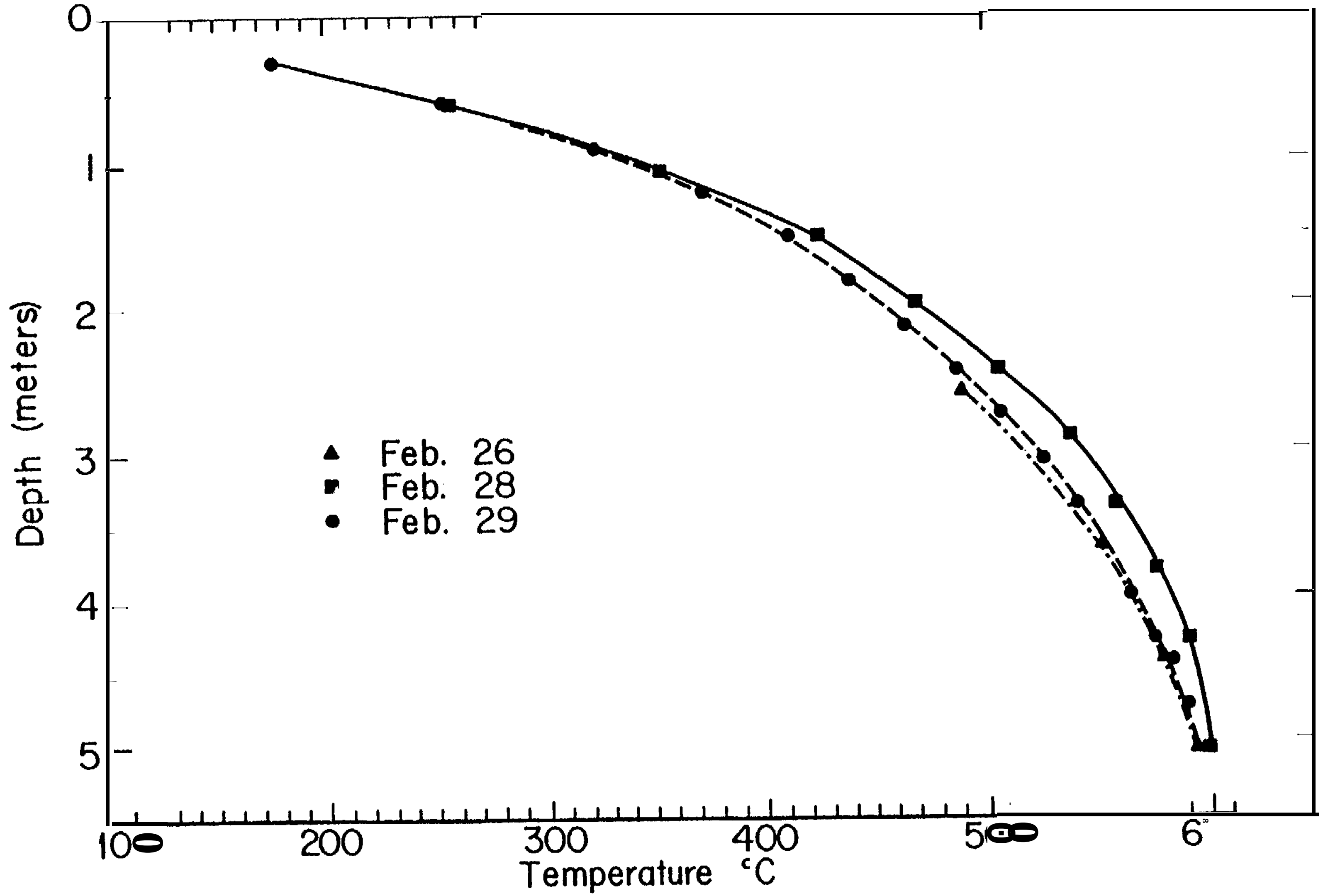


Figure 30. Temperature profiles measured a few weeks after depos tion of the pyroclastic flows east of Burr Point; temperature test site is located on new flow shown in Figure 19d near the position of the old beach line.

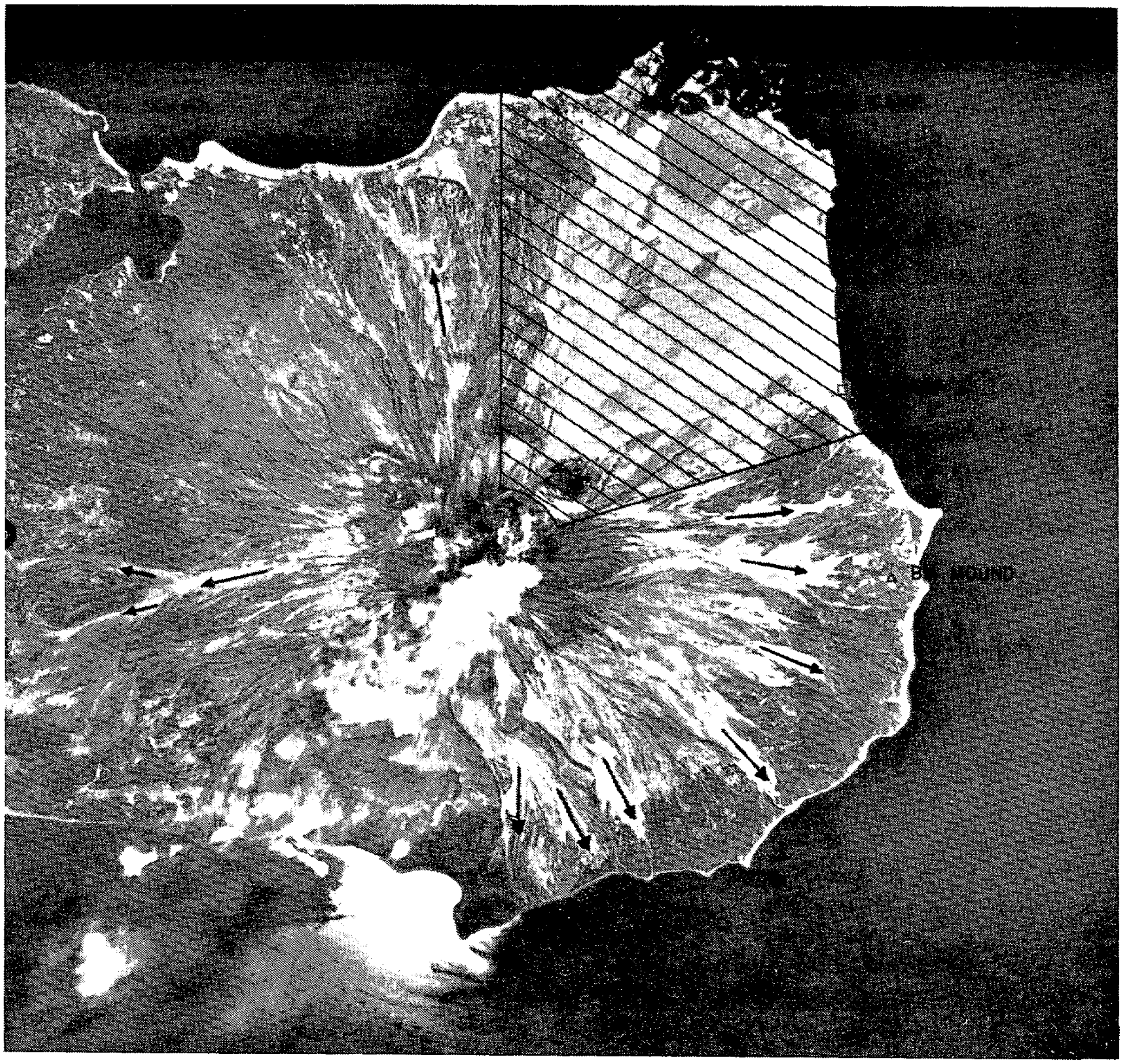


Figure 31. Vertical photograph of Augustine Island, taken by the National Ocean Survey on June 11, 1976, showing distribution of the light colored 1976 pyroclastic avalanches and debris flows (arrows and ruled area). The lines of the ruled area indicate profiles along which the topography was digitized on high resolution vertical imagery to obtain an accurate volume estimate of the 1963/64 and 1976 deposits in that sector of the volcano.

Figure 32. Close-up of the 1976 pyroclastic flow deposits on the northern flank of Augustine Volcano. The sulfur-stained white-appearing area at the base of the steaming 1976 dome is shown in Figure 33 (photograph by H. -U. Schmincke).

Figure 33. "Hells Gate" at the base of the 1976 lava dome. Pyroclastic avalanches have eroded a U-shaped channel. Two persons stand on old inversely graded pyroclastic flow deposits (the person on the left is Dr. David Johnston who completed his Ph.D. on the petrology of Augustine Volcano in 1978 and was recently killed in a tragic accident by a hot blast from Mt. St. Helens, Washington, on May 18, 1980 (photograph by H.-U. Schmincke).

During our February visit we also managed to re-establish a new three-station seismic arrayon the island, after all but one of the original 5 seismic stations had been buried by pyroclastic flows.

Little seismic or eruptive activity was observed from February 16 to early April, except for some shallow earthquake swarms from March 15 to 25. However, in early April, we began to record peculiar wave trains with no distinct phases and a cigar-shaped wave envelope, which we later learned to recognize as the seismic signature of pyroclastic avalanches rumbling down the mountain. The number of these events increased dramatically up to April 12. During the peak activity, avalanche after avalanche cascaded off the dome almost continuously, as it underwent renewed growth. Bill Koplin and Howard Feder from the University of Alaska's Institute of Marine Science eyewitnessed this avalanche activity on the evening of April 12 and throughout April 13 from aboard the Hawaiian research vessel "Moana Wave".

> "The avalanches were glowing in a ruby-colored red sometimes splitting up in 2 or more branches and sometimes merging again as they come down at great speed the northeast sector of the volcano. Soon they would cool and become black and then split open again and glow. At dusk on April 12, avalanches succeeded each other at a rate of one every 10-15 minutes. All of these avalanches fell from the north-face of the dome as a mass of brightly-colored material falling down a vertical precipice and then following down a chute. Clouds of dust and ash would spread out like a reversed cone and then expand above the mountain. There was a tremendous amount of smoke and dust hanging over Cook Inlet and the summit-had a continuous large white plume".

The seismic activity and by implication dome growth tapered off by April 19 and returned to normal by April 24.

A new photogrammetric topographic map of the summit region was produced from photography taken on August 25, 1976 (Figure A2, Appendix 1) which shows that the dome eventually grew to a height of 4,011 feet

(1,226 m). A new South Peak now makes up the summit with a height of a little over 4,100 feet (1,250 m). Thus, the volcano lost about 200 feet (61 m) in elevation since 1964.

Figure 34 shows the distribution of the 1976 eruptive deposits. The main thrust of the debris flows is again northeast and east, with some flows directed toward the northwest and southwest. Data for this figure came mainly from vertical aerial photographs taken in the summer of 1976. Numerous additional oblique photographs of the 1976 eruption were used to supplement the vertical photography. Reconnaissance field surveys of the 1976 eruptive deposits have also been done, primarily on the northern and northeastern flanks of the volcano. Johnston, shortly before his tragic recent death on Mt. St. Helens, was preparing a new detailed map of the Augustine ejects based on field mapping between 1976 and 1979. We hope to be able to complete the map for him for the final report.

1976-80 Activity - Current State

Following the renewed growth episode of the new summit lava dome in April, 1976 only occasionaly minor ash eruptions occurred. Chuck Berns, an Anchorage bush pilot photographed an ash and steam explosion originating at the eastern base of the dome on April 11, 1977, at 17:15 AST. The plume rose to a height of about 300 m above the summit. David Stone overflew the snow covered volcano on April 6, 1977, and took a photograph which clearly shows that the northeastern pyroclastic avalanche deposits stayed snow free probably throughout the winter 1976/77 due to their internal heat. Bill Feetham eyewitnessed a larger ash explosion on May 14, 1977, 21:00-21:30 ADT; the plume trailed off up the inlet to a distance of about 30 km. The island was largely obscured due to ash fallout and *on* the following morning, May 15, a “line of smudge

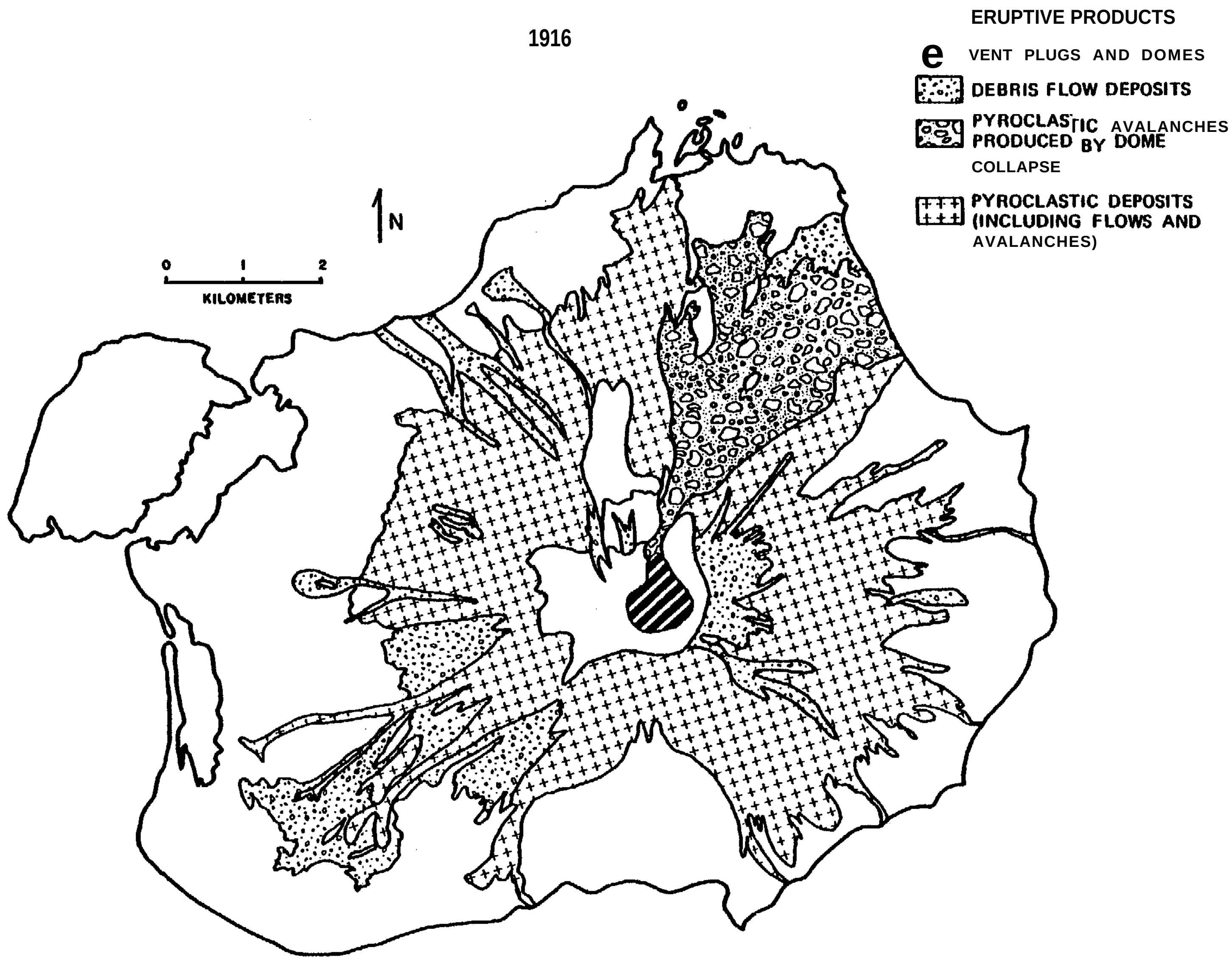


Figure 34. Distribution of the 1976 eruptive products.

and steam" extended toward Chinitna Bay at the peak level (1,200 m). The eruption also produced a seismic signal on Augustine Island stations. Undoubtedly many other such eruptions occurred in 1976 and up to 1977, but none of these caused any ash. falls on the Kenai Peninsula.

*- In August, 1978, David Johnston made the first ascent of the new summit lava dome and estimated the temperature of the very active fumarole at the base of the apical spine (Figure 35) at about 650°C (Johnston, 1979C). His temperature measuring equipment went off scale and the temperature estimate is based on observing a faint red glow. In the following summerof 1979 Johnston (personal communication) measured the same fumarole again with appropriate high temperature equipment and found it to be stil as hot as 754°C. He also collected gas which still contained abundant SO_2, CO_2, and halogens (chlorine and fluorine). Based on his Augustine gas data, Johnston (1980) discussed the volcanic contribution of chlorine to the stratosphere and its impact on the ozone layer.

No major volcanogenic earthquake swarm has been recorded since April 1976, even thoughwe have continuous data since then. We do record occasional shallow events of small magnitude ($<M_L=2$), located in the cones central plumbing system just below or above sea level.

The surface layers of the pyroclastic flow deposits have now cooled to the ambient temperature. The summit dome continues to cool and still emits a steady plume of white vapor, sulfur, carbon dioxide and halogen gases.

As a summary, Figure 27 shows 4 northern views of the volcano, illustrating how dramatically the various eruptions changed the appearance of the volcano.

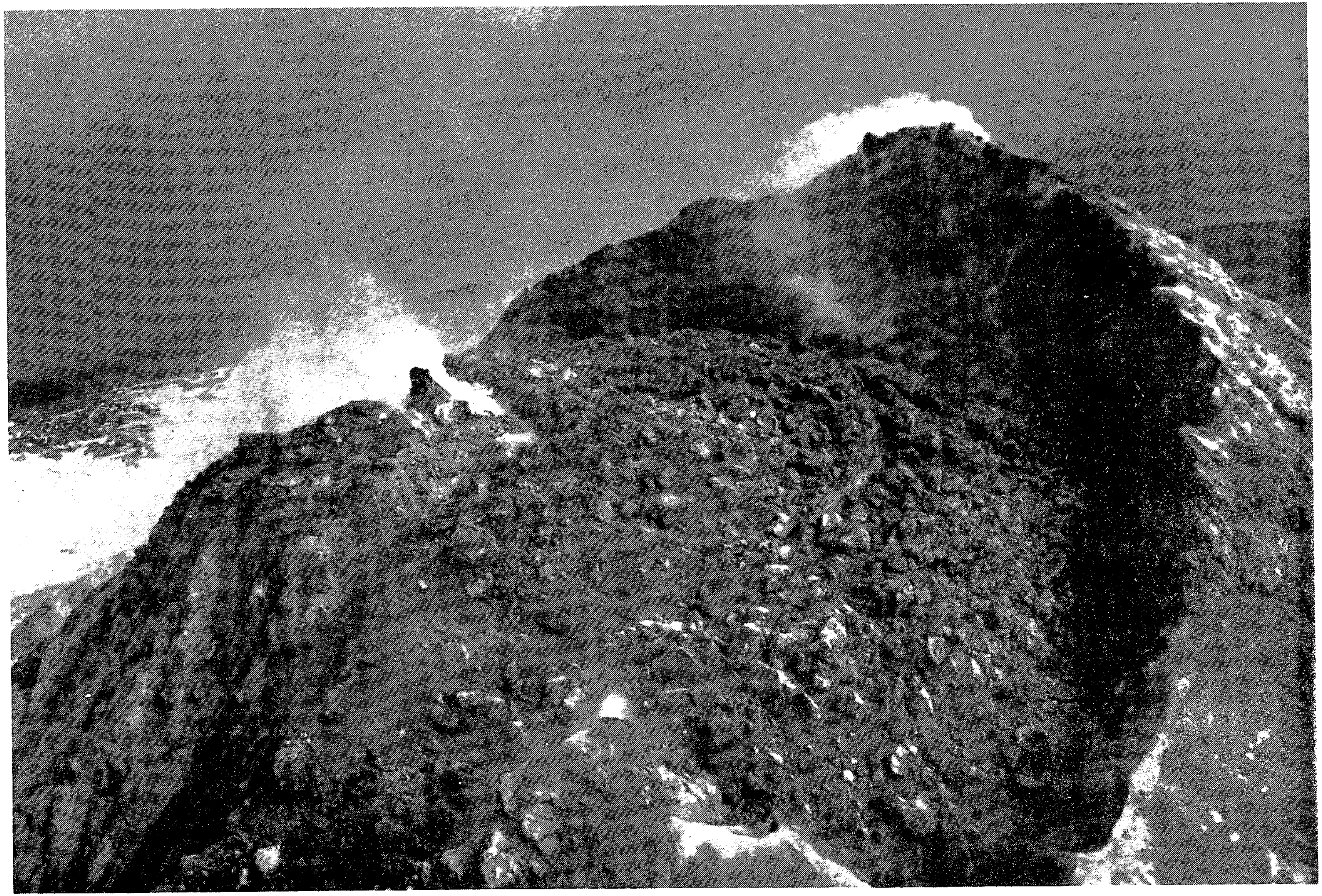


Figure 35. Close-up of the 1976 lava dome within remnant of the '64 dome. Fumarole temperature at base of summit spine of '76 dome was 754°C in August 1979 (David Johnston, personal communication).

ERUPTIVE PRODUCTS

Future eruptions of Augustine Volcano are expected to be similar to previous eruptions in terms of eruptive style and deposits. Magma composition has remained relatively constant throughout most of Augustine's history with a silica content averaging 60 percent. To a large extent, the silica content determines the style of eruption and the nature of the eruptive products. Thus, a relatively constant silica content for Augustine magmas suggests future eruptions should be similar to the ones in the past.

Silica controls the eruptive style. To quote from Francis's (1976) popular text "Volcanoes":

> Composition dictates melting temperature,
> temperature dictates viscosity,
> viscosity dictates explosive potential of eruption,
> explosiveness of eruption dictates whether lavas or pyroclastics are produced.

Silica forms a three dimensional framework structure in magmas with oxygen and silica atoms joined in large polymers. The higher the silica content of the magma, the larger the silica polymers. Flowage of the magma is related to the size of the silica polymers, the larger the polymers the slower the flowage of the magma and hence the higher the viscosity. Silica content is also related to the temperature of a magma and this also effects magma viscosity. For any given magma, the lower the temperature, the higher the viscosity. Silica-rich magmas (70-75 percent SiO_2) melt and solidify at relatively low temperatures, while silica-poor magmas (50-55 percent SiO_2) are characterized by relatively high temperatures. Thus, silica-rich magmas have high viscosities due to low temperatures and high silica contents.

Augustine magmas have an intermediate silica content and are quite viscous. The eruptions are highly explosive and commonly produce tephra (fragmented material) and pyroclastic flows. Lava flows are not a common product of Augustine eruptions, because the viscous Augustine lavas do not tend to flow but rather form vent-filling domes. Debris flows formed by water carrying volcanic debris down the flanks of Augustine Volcano are common because of the steep slopes, an abundance of fragmental material and the moist climate.

Petrology

Andesite and dacite are the dominate volcanic rocks on Augustine Island. These intermediate lavas are in the form of pumiceous pyro-elastic deposits, massive domes and a single lava f"low on the northern flank of the volcano. Debris flows are composed of both pumiceous and massive varieties of andesite and dacite and are the most widespread deposits on Augustine Island. Mineralogically, the andesites and dacites are similar. Plagioclase, hypersthene and augite are the most abundant phenocrysts in the lavas. In addition, olivine and basaltic hornblende are found in the andesites. Dacites often have a glassy groundmass resulting in a vitrophyric texture. Andesites are more crystalline than dacites and have a fine-grained matrix.

Inclusions and bands of andesite within dacite are common in the Augustine lavas. Microscopic examination of the contact between andesitic bands or inclusions and the host dacite shows that phenocrysts from the andesite have been added to the dacite, suggesting mixing between the andesite and dacite. Such evidence for mixing is common in intermediate talc-alkaline volcanic rocks and is fairly common in the Augustine lavas.

Initial volcanism on Augustine Island apparently involved basaltic and rhyolitic lavas (Johnston, 1979a). On the south side of Augustine Island, Johnston describes rhyolite sands and basaltic hyaloclastites deposited on a glaciated surface of Tertiary and Mesozoic sedimentary rocks. Johnston (1979a) suggests the volcanism on Augustine Island began about 17,000-13,500 years B.P. and was initially bimodal basalt-rhyolite. However, the eruptive products quickly became more intermediate andesites and dacites with evidence of mixing between the felsic and mafic components. This pattern of hybrid intermediate magmatism has continued from early in the history of Augustine Volcano to the present.

Chemistry

The consistency in the mineralogy of the Augustine andesites and dacites is reflected in the chemistry of the volcanic rocks. Table 1 gives the average of22 analyses of volcanic products from Augustine Volcano. Included within these 22 analyses are samples of volcanic ash and bombs, massive andesites and dacites from lava flows and domes, and pumiceous lavas from pyroclastic deposits. The analyses represent not only historical eruptive deposits but also prehistoric lavas. Despite the time span, the variety of eruptive styles and products represented in the analyses,. the bulk compositions are restricted to the dacite-andesite range (Table 1). The range of compositions reported in Table 1 is about the same as the range of reported compositions from the 1976 eruption (Kienle and Forbes, 1976). Thus, magma composition appears to have remained relatively constant throughout the history of Augustine Volcano.

Average composition of the Augustine lavas is intermediate between dacite and andesite. The silica, iron and sodium contents of the average

Table 1. Average composition of volcanic products from Augustine Volcano. Basedon results of this study, Becker (1898), Detterman (1973), and Kienle and Forbes (1976). Average andesite and dacite from Nockolds (1954).

	Average[1] of Augustine Lavas	Observed Range of Augustine Lavas	Average Dacite[2]	Average Andesite[2]
SiO_2	60.33	56.27-64.20	63.6	54.2
TiO_2	0.61	0.50-0.75	0.6	1.3
Al_2O_3	16.73	15.70-17.42	16.7	17.2
FeO*	6.02	4.80-7.37	5.2	9.0
MnO	0.13	0011-0.15	0.1	0.1
MgO	4.04	2.60-4.86	2.1	4.4
CaO	7.45	5.30-8.61	5.5	7.9
Na_2O	3.81	2.80-5.57	4.0	3*7
K_2O	0.93	0.72-1.10	1.4	1.1
P_2O_5	0.13	0.05-0.19	0.2	0.3

*FeO inclues Fe_2O_3

[1]average of 22 analyses

[2]from Nockolds (1954)

Augustine lava are also intermediate between dacite and andesite, titanium and aluminum contents are about the same as dacite and the magnesium, calcium and potassium contents are very similar to the average andesite defined by Nockolds (1954). These compositional relations reflect the hybrid nature of the Augustine lavas.

Chronology

As discussed earlier, Augustine Volcano has erupted in 1812, 1883, 1935, 1963 and 1976. The time interval between historic eruptions of Augustine Volcano has shortened with each successive recorded eruption (Figure. 36). Extrapolation of the trend in the recurrence interval shown on Figure 36 shows the interval between eruptions becoming zero in 1983. The significance, if any, of this projection is not presently understood. Studies of prehistoric Augustine eruptions utilizing C^{14} geochronology are currently underway and should help to evaluate the pattern of eruptive interval shown in Figure 36. Based upon the historic eruption record, Augustine has had two to three eruptions per century for the last two.

Preliminary studies of prehistoric Augustine eruptions indicate a similarly active eruptive pattern. Several stratigraphic sections have been sampled on the eastern flank of Augustine Island. The oldest exposed unit in the sections is a semi-consolidated poorly-sorted mud-flow deposit of andesite and dacite fragments in a fine-grained matrix; the flow extends offshore. A mat of contemporary tundra covers the top of the sections. Near the base of the tundra mat is a light-gray volcanic ash layer about three cm thick, representing the 1912 Katmai eruption. Between the Katmai ash and the base of the section are a series of eight volcanic ash and lapilli layers (tephra) interbedded with paleosoils.

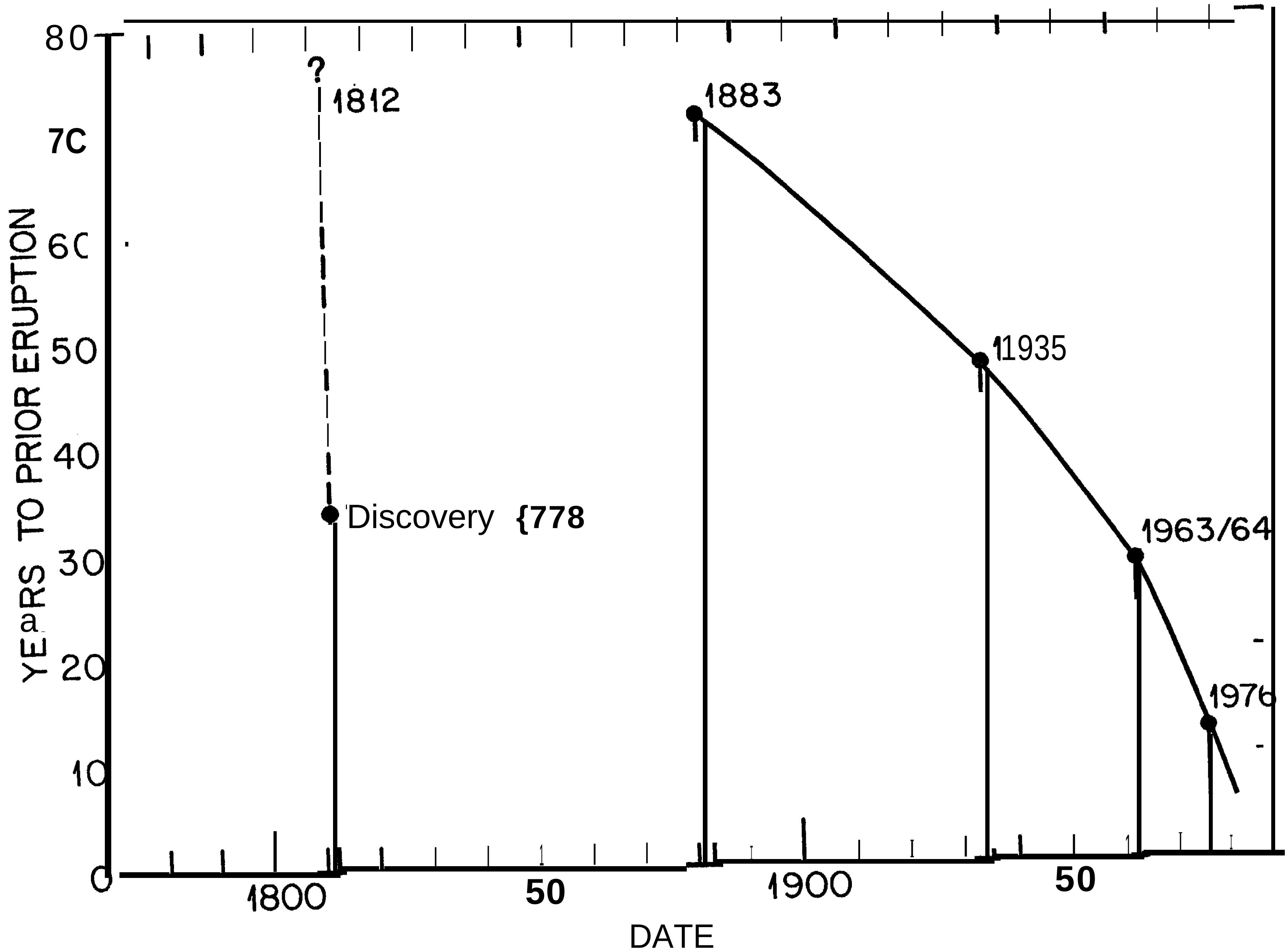


Figure 36. An apparent shortening of repose time between eruptions for at least the past 4 **Augustine eruptive** cycles.

Each of the ash layers is thought to represent an eruption of Augustine Volcano because the mineralogy and chemistry of the ash layers is similar to other Augustine eruptive deposits and the volcanic fragments are rather coarse suggesting a very close source. Paleosoils near the base of two different sections have been dated by the C^{14} technique and yield ages of 1,470 ± 160 years B.P. and 1,500 ± 155 years B.P. Thus, during the last 1,500 years Augustine has erupted at least eight times in the period 400 to 1912 A. D., and three times since 1912. It is extremely unlikely that the tephra layers sampled in these sections represent all of the eruptions of Augustine Volcano within the last 1,500 years. Based upon the previous discussions of volcanic eruptions and deposits on Augustine Island, it is obvious that one eruption cycle does not necessarily cover the entire island with volcanic debris. Thus, the eight eruptions in the sections studies represent a minimum and the actual number of eruptions within this 1,500 year time span may be two or three times greater. Augustine has been an active volcano for at least the last 1,500 years, probably with an average of one to three eruptions per 100 years. This pattern of active volcanism is expected to continue.

Eruption Volumes

Andesitic melts are derived from the upper mantle or the base of the crust (at 50 to 100 km depth) with subduction somehow triggering the generation of the melt. The details of this process are still not understood but the genetic relationship of island arc volcanism and plate subduction is clearly established. Once generated, the melts rise buoyantly as diapirs to shallower levels in the crust (e.g. Marsh, 1979), where they maybe stored in shallow reservoirs, the shallowest of which will probably feed the eruptions. We have geophysical evidence that such a shallow reservoir exists beneath Augustine Volcano, probably shallower than 3 km beneath the summit. Presumably, each eruptive cycle drains the chamber more or less completely and during the repose time between eruptions the chamber gets recharged by new melt from depth. Again, the details of this recharge mechanism are not yet understood. The size of the reservoir is obviously an important parameter controlling the magnitude of the eruption. Eruption volumes are an indirect indicator as to how big the eruption feeding reservoir might be and thus as to what magnitude eruption it may be able to produce. In the following we would like to demonstrate the constancy of eruption volumes at Augustine which together with the unchanging chemical composition of the ejects over the past 1,500 years suggests a steady state plumbing system, involving a relatively small shallow storage reservoir and a fairly regular charge-discharge cycle.

In Table 2 the estimated bulk volume of the ejects from the 1976 eruption is about 0.4 km^3, of which 0.06 km^3 are flows on the island itself and the rest is tephra. We arrived at this estimate by digitizing the pre- and post-eruption topography of the sector most affected by debris flow activity, the northeast sector of the Island (Figure 31) and by using conservative estimates of the total thickness of tephra accumulation for the area that was affected by ash falls (Figure 15). Condensing the 0.4 km^3 of expanded material into solid rock or magma would require a storage chamber volume of about 0.2 km^3, equivalent to a sphere of 360 m radius.

Detterman's (1968) estimate of the 1963/64 debris flow accreted on the island is 0.09 km^3 (a crude estimate that seems somewhat high, when compared to the 1976 eruption).

Table 2 - Volume of the 1976 Eruption

	Area (km^2)	Thickness	Bulk Volume (km^3)	Reduction Density Ratio	Equivalent Solid Rock Volume
Island Flows					
NE-sector	15.6	-37 to +35 m[1]	0.049		
SE-sector	2.6	~ 2 m	~ 0.005		
SW-sector	1.6	~ 1 m	~ 0.002		
NW-sector	1.0	~ 1 m	~ 0.001		
		Total	0.057	1.652/2.$	0.038
Mass Loss					
1964-1976 domes			-0.009[4]	2.32/2.5	-0.008
Ash Falls, January 22-25, 1976- later ash falls negligible					
Upper Cook Inlet & Gulf of Alaska	182,188	0.5 mm[5]	0.091	1.366/2.5	0.050
Central Cook Inlet & Gulf of Alaska	55,625	~ 1 mm[2]	0.056	1.36/2.5	0.030
Lower Cook Inlet	37,188	5 mm[7]	0.186	0.998/2.5	0.074
Augustine Island	133	50 Inn?	0.006	0.99/2.5	0.002
		Total	0.339		0.1 6
		Total Eruption	0.387		0.186

1 Near the top of the fan the flows eroded; the main accumulation was near the center and bottom of the fan.

2 Laboratory determination of two 1964 dune samples gave 2.3 g/cm^3; for flows we crudely assume ,50% dome debris and 50% pyroclastics, i.e., (2.3 + 0.99)/2 g/cm^{-3}.

3 Mt. Hood andesi te at 800°C (Murase and McBirney, 1973, p. 3572, Fig. 10).

4 $V = 1/6\ \pi\ h\ (3\ a^2 + h^2)$, where a = 250 m, h = 89 m (4,304 -4,011 feet).

5 Total ash thickness reported from Anchorage (Miller, 1976). '

6 Laboratory determination of ash sample, 60-85 mesh or 0.175- 0.212 mm.

7 Ash thickness, measured at Oil Bay, 35 km N of Augustine.

8 Laboratory determination of Oil Bay ash sample.

9 (Johnston, 1978.)

The total volume of volcanics making up the visible cone of Augustine is about 15 km^3 and there may be an additional 1 to 2 km^3 of volcanics offshore. Assuming that 0.05 to 0.1 km^3 of new material is accreted on Augustine Island each time the volcano erupts it would take 160 to 340 eruptions to build the visible cone and offshore flows, or given an age of the volcano of 13,500 to 17,000 years (Johnston, 1979a) about 0.5 to 1 eruptions per century. For the past 2 centuries the recurrence rate was 2.5 eruptions per century, a number which is a factor 2.5 to 5 higher than the recurrence rate derived by assuming a steady state process. The argument is no doubt over-simplified but it nevertheless demonstrates that Augustine probably never had an eruption which produced a volume greater than 1 km^3 and that repose times between eruptions may have been greater in the past.

It may be instructive to contrast these numbers to eruption volumes produced by very large eruptions such as Krakatoa in Indonesia, 1883, or Mt. Katmai, Alaska, 1912. These are relatively rare events (a few per century in the world) and involve both bulk eruption volumes (not reduced to equivalent dense rock) of order 10 km^3 or more. Katmai erupted an ashflow of 11-15 km^3 in volume and $\sim$20 km^3 of tephra in $\sim$60 (!) hours (Hildreth, 1979) while the Krakatoa eruption involved about 18 km^3 of ejecta. When such' large, so called paroxysmal, eruptions occur near populated areas the loss of life can be great (about 36,000 casualties due to volcanogenic tsunamis for Krakatoa) and often there are far reaching or even worldwide climatic effects (acid rain on Chicago following the 1912 Katmai eruption Griggs, 1922). The 79 A.D. Vesuvius and 1980 Mt. St. Helens eruptions produced several km^3 but probably less than 10 km^3 of ejects.

All historic and also prehistoric Augustine eruptions have produced eruption volumes that are 2 orders of magnitude smaller than either Katmai or Krakatoa and 1 order of magnitude smaller than Mt. St. Helens or Vesuvius. In fact, a single Katmai eruption could produce the entire Augustine cone, while it takes a few hundred typical Augustine eruptions to form the same volume.

In summary, considering the youthfulness of the volcano and its apparent steady-state behavior over its short life span of no more than 13 to 19,000 years, it seems highly probable that the eruptive pattern will stay the same in the near future (few 100 years) and furthermore> it seems unlikely that Augustine in its present state of development could produce a very large, e.g. Katmai-sized eruption. Future eruptions are likely to follow the eruptive patterns of the well documented historic eruptions, with small ($\sim$ 0.5 km^3, flows plus tephra) volumes of magma being erupted 2-4 times per century.

HAZARDS

The chief hazards from future eruptions of Augustine volcano will be pyroclastic flows and nuées ardentes (glowing clouds) which may continue out to sea. Tsunamis capable of crossing Cook Inlet to the eastern shore may be generated by this process. Tephra (airborne volcanic debris) fall will affect the island and a large area offshore, the dispersal of finer airborne material depending strongly on the prevailing wind conditions. Extreme dustiness can be expected for tens of km downwind from the volcano even when the volcano is not actively erupting, as freshly fallen fine ash is easily picked up by winds. Lava flows will almost certainly reconfined to the island itself. Because Augustine Island is so small (6 km radius) there are simply no sites on the island itself that would be safe to erect permanent structures unless they were underground. However, such underground structures could easily get buried.

Pyroclastic Flows

Pyroclastic flows are air-cushioned avalanches of hot, dry rock debris. They may be generated either by explosive eruptions (a directed blast as in the Pelée type or a vertical blast and subsequent collapse of the eruptive column as in the Soufrière type) or the collapse of a volcanic dome (as in the Merapi type). Cartoons of each of these three eruptive mechanisms are shown in Figure 29. Large volumes of hot air and other gases are evolved within pyroclastic flows and this, together with the force of the volcanic blast and the air cushion trapped beneath the flow accounts for their great speed (180 Ion/h for the small flow and nuée ardente observed on February 8, 1976;Figure 26) and mobility. Pyroclastic flows move as density currents flowing down the slope of the volcano. Generally, topography influences the velocity and direction of the pyroclastic flows. Flows move rapidly down the steeper flanks of the volcano and slow down on gentler slopes. However, pyroclastic flows can move for considerable distances over horizontal surfaces due to the initial high *velocity* and the cushioning effect of the trapped air layer under the flow. Locally, pyroclastic flows may even move uphill for short distances. Miller (1977) described the spectacular mobility of large ash flows around Aniakchak and Fisher calderas on the central Alaskan Peninsula and Unimak Island:

> "At Aniakchak ash flows swept down glaciated valleys on the south side . . . . . crossed a broad lowland with an altitude of less than 35 m, and continued on through passes as much as 260 m high . . . into the Pacific Ocean, a distance of some 50 km".

Smaller pyroclastic flows will tend to follow topographic lows such as stream valleys.

Pyroclastic flows consist of coarse basal glowing avalanche and a high billowing hot ash and dust cloud. The majority of the material involved in pyroclastic flows is juvenile volcanic material either just erupted from the vent or from the collapse of an emerging dome. Blocks in the basal avalanche unit may be quite large (up to ten meters or more in diameter). Basal avalanches are generally confined to the bottoms of valleys while the ash cloud that rises above the avalanche spreads out both laterally and vertically. Under certain conditions the glowing ash cloud separates from the basal avalanche, as occurred on May 8, 1902, during the eruption of Mt. Pelée on the island of Martinique, West Indies, Macdonald (1972), summarizing Anderson and Flett's (1903) and Lacroix's (1904) account of the eruption, states that on that day a great black cloud of ash was erupted to several km above the volcano and simultaneously a horizontal blast was directed toward the city of St. Piérre through a notch in the crater wall. Initially, the basal glowing avalanche and associated nuée ardente traveled together following the headwaters of Rivière Blanche, but at Morne Lenard the avalanche turned 90 degrees to the west, while the nuée detached itself and proceeded along the original course towards St. Pierre obliterating it and nearly all of its 30,000 inhabitants, all in less than 2 minutes after the eruption began (Figure 37).

The city lies 6 km from the volcano, hence the velocity of the cloud must have been of order 150-200 km/h. The hot blast that struck the city was so powerful that masonry walls 1 m thick were knocked over and a 3-ton statue was carried 12 m from its base. Most of the ships in the harbor were blown over, sunk or set afire. The bodies of people were intensely burned and many in the north end of town closest to the volcano were stripped of their clothing by the force of the blast. The nature of injuries indicated that the sudden heat was intense enough to turn water in human tissue to steam {order 600 to 1000°C) and the temperature was also high enough to soften glass. Bodies with their clothing intact were often severely burned underneath. Relatively little debris was left in the city after the cloud passed, about 30 cm, indicating that it consisted mainly of hot gas and dust.

In many respects Augustine is very similar to Mt. Pelée:

(1) Augustine is now 4,100 feet high, Pelée 4,428 feet.

(2) Augustine erupted in the past 200 years with an average repose time of 41 years, Pelée 44 years.

(3) Eruption volumes and eruption style (dome growth and associated pyroclastic flow activity) and the geochemistry is very similar.

(4) The craters of both volcanoes are breached, the breach providing the preferred avenue for pyroclastic flows.

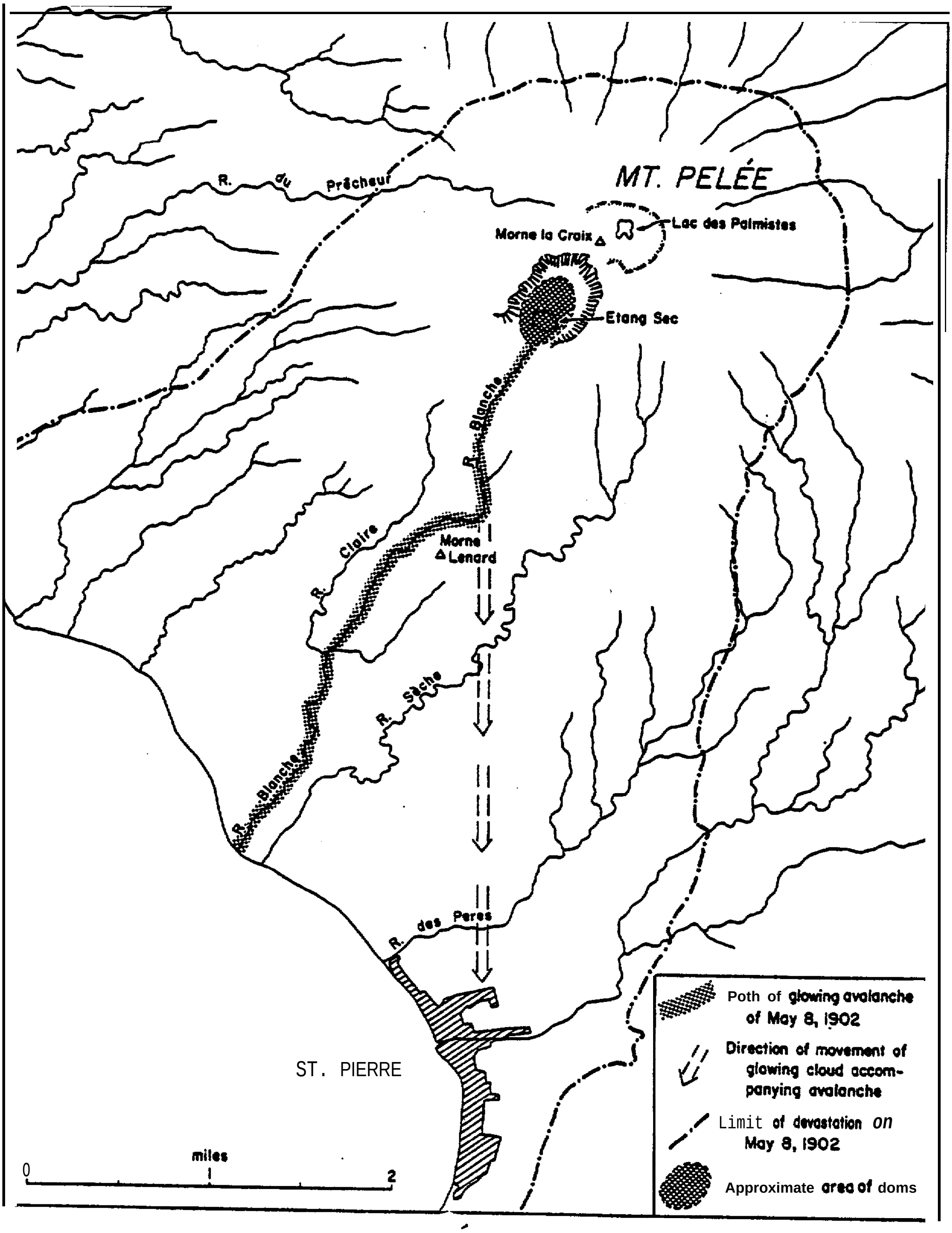


Figure 37. Map illustrating how nuees ardentes can detach themselves from their basal pyroclastic (glowing) avalanches and proceed independently, as during the disastrous destruction of the City of St. Pierre, Martinique, Lesser Antilles, during the May 8, 1902 eruption of Mt. Pelée. The pyroclastic avalanche followed the Rivière Blanche to its mouth, while the nuée continued straight toward the city (taken from Macdonald, 1972, p. 144).

(5) The distance of thevent from the nearest seashore is 4 km for Augustine, 5 km for Pelée.

Pelée can therefore serve as a direct analogy for many eruptive phenomena at Augustine.

Other wel 1 documented glowing avalanche eruptions occurred at Mt. Lamington, Papua, in 1951 (Taylor, 1958) and Mt. Mayon, Phillipines, 1968 (Moore and Melson, 1969). The only additional phenomenon that needs to be discussed here is that the pyroclastic flows at Mt. Mayon (Soufrière type) produced a sear zone a few 100 m to 2 km beyond the flow termini. Within the seared zone all animals were killed and the tropical vegetation was charred or shriveled. Moore and Melson (1969) believe that cold shockwaves, uprooting thick palm trees, preceeded the hot blast of the nuée that later charred the bottom of" the roots of the trees, implying that cold air is compressed and pushed forward by the rapidly advancing nuée.

Obviously, the hot ash, dust and gases in the nuée ardente are the most hazardous elements in pyroclastic flows. The high temperatures in these clouds and their great speed devastate life and property in their paths. A zone of high temperature air and gas extends out well beyond the areas of major debris deposition and greatly expands the hazard zone associated with pyroclastic flows. No structures or life would survive in the avalanche zone itself.

Eruptions of Augustine Volcano are characterized by pyroclastic flows associated with all three mechanisms, directed blasts and the collapse of a vertical eruptive column or a volcanic dome. Initially, Augustine eruptions are vent-clearing and may involve powerful low angle or vertically directed blasts. Later in an eruptive episode, a dome is commonly emplaced in the vent and subsequent collapse of portions of the dome can produce additional pyroclastic flows of somewhat different composition as we have discussed for the 1976 eruption.

Deposits of pyroclastic flows are found on all parts of Augustine Island (Figures 3, 7,8, 11 and 34). In fact, the island grew to its present size principally by accretion of such avalanche deposits.

Deposits from both the basal avalanche and nuée ardente associated with the pyroclastic flows are found practically everywhere on Augustine Island. Avalanche deposits are very poorly sorted and contain particles ranging in size from less than one millimeter to tens of meters in diameter. The material in these deposits is dominated by highly vesicular volcanic glass with a few percent of plagioclase and pyroxene phenocrysts.

Knowledge of damage to structures on Augustine Island caused by pyroclastic flows is limited to the effects of the 1976 eruption on research facilities at Burr Point and on a small structure on the northwest coast of the island. Both of these areas were on the edge of the paths of the 1976 pyroclastic basal avalanches and were subjected primarily to the effects of hot blasts and nuées ardentes. One of these blasts completely collapsed the small hut on the northwest coast of the island. As discussed before, the corrugated aluminum buildings at Burr Point were dented and holes, one 15 cm in diameter, were punched by falling debris in the aluminum roof. Temperatures were high enough to melt plastic objects and burn mattresses at Burr Point. Grass and tree stumps were charred along several kilometers of coast line at the northern and southwestern shores of the island.

One of the main unanswered questions at Augustine is how far across the water nuées ardentes would travel and how far the basal avalanche would proceed out to sea. Again we have to call on the Mt. Pelée analogue, which is a particularly good one since the volcano height and distance to the shoreline are so similar to Augustine. During other eruptions besides the disastrous one of May 8, 1902 several nuées ardentes traveled as far as 8 km offshore after descending 6.5 km down the 4,428 foot high flank of the volcano, Anderson and Flett (1903) who eyewitnessed two such nuées on the evening of July 9 from a ship lying off Carbet, a small town 4 km south of the devastated city of St. Pierre, gave the following description:

> First nuée: "In the rapidly-fallin.g twilight we sat on deck. ... when our attention was suddenly attracted to a cloud which was not exactly like any of the steam cauliflowers we had hitherto seen. It was globular, with a bulging, nodular surface; . ..darker in colour, being dark slate approaching black. ..Its behaviour, however, was unique. It did not rise in the air, but rested there, poised on the lip of the fissure, for quite a while as it seemed,. ..it was too heavyto soar up in the air like a mass of vapour, and it lay rolling and spouting on the slopes of the hill. The wind had no power over it,. ..slowly we realised that the cloud was notat rest but was rolling straight down the hill, gradually increasing in size as it came nearer and nearer. ..We helped the sailors to raise the anchor and, setting the head sails, we slipped away before the wind. By the time the mainsail was hoisted we had time to look hack, but now there was a startling change. The cloud had cleared the slopes of the hill. It was immensely larger, but still rounded, globular, with boiling, pillowy surface, pitch black, and through it little streaks of lightning scintillated. It had now reached the north side of the bay, and along its base, where the black mass rested on the water, there was a line of sparkling lightings that played incessantly. Soon, however, it seemed tc nose its velocity; its surface became. less agitated, it formed a great black pall, with larger, less vigorous, more globular, bulging convolutions. Evidently its violence was spent, and it was not to strike us; it lay almost like a dead mass on the surface of the sea.
>
> For 20 or 30 minutes we sailed along with a gentle breeze from the east,. ..then the wind fell away, and it was practically a dead calm.''. . .
>
> Second nuée: "Suddenly a great yellow or reddish glare lit up the whole cloud mass which veiled the summit. ..Then from the mountain burst a prolonged angry growl, not a sharp detonation. . .
>
> Then in an instant a red-hot avalanche rose from the cleft in the hillside [notch in the crater], and poured over the mountain slopes right down to the sea. It was dull red, and in it were brighter streaks, which we thought were large stones, as they seemed to give

off tails of yellow sparks . . . The main mass of the avalanche was a - " darker red, and its surface was billowy like a cascade in a mountain brook. Its velocity was tremendous. ..The red glow faded in a minute or two, and in its place we now saw, rushing forward over the sea, a great rounded. boiling cloud, black, and filled with lightnings. It came straight out of the avalanche,. ..coming straight over the water directly for us, where we lay with the sails flapping idly as the boat gently rolled on the waves of the sea.

The cloud was black, dense, solid, and opaque, absolutely impenetrable, like a mass of ink. It was globular as seen end on, very perfectly rounded, but covered with innumerable minor excrescences, rounded, and filled with terrific energy. They shot out, swelled, and multiplied till the whole surface seemed boiling;... the cloud drove forward without expanding laterally to any great extent... The cloud lay on the water and sped on horizontally...

The display of lightning in the cloud was marvellous...we were at once reminded of the narratives given us by survivors in St. Vincent, in which it was stated that when the black cloud rolled down upon the sea it was filled with fire. [The Soufrière in St. Vincent erupted simultaneously with Pelée].

Nearer and nearer it came to where our little boat lay becalmed, right in the path of its murderous violence. ..But in a minute a slight puff of wind came from the south-east, very gentle, but enough to ripple the water and fill the sails. We had drifted out from the shore, so we gave our boatmen instructions to keep the boat close-hauled, and drawn in to the land, as the cloud was passing more to the westward. Then when we looked at the cloud again; it was changed, it showed no more the boiling, spouting, furious vigour, but the various rounded lobes in its point swelled slowly and to greater size, while fresh ones did not shoot forward,... we thought it was a mile off, or rather more.

It now lay before us nearly immobile, a gigantic wall. ..This lasted a few minutes, and the folds became flatter and less convex. . . The dust was sinking, and the pale steam...was following its own natural tendency to ascend...

The steam cloud crept southward, and was soon directly over our mast-head, traveling with a velocity of perhaps 20 miles an hour...

As the cloud reached the zenith a hail of pebbles fell in the sea and on our decks. We picked up the first that fell. It was about the size ofa chestnut, and was cold to the touch, so we knew that we were safe. Then smaller pellets rattled on our decks, like a rain of peas or small shot. A little afterward the fine gray ash came in little globules moist and adherent. ..They were not warm, and there was a slight but noticeable smell of sulphurous acid,..

The second black cloud did not differ in appearance from the first, except that it was larger, had a far greater velocity, and swept out at least twice as far across the sea...

No blast struck us -- in fact we were becalmed -- it seemed that when the black cloud ceased the blast was also over. Nor did the sea rage around us as some have described who were overtaken by the dust storm. [e.g. the account of Captain Freeman of the "Roddam", which barely escaped the May 8 disaster. He stated that a great rush of wind greatly agitated the sea; the "roaring" sea tossed ships back and forth].

Similarly, the one or more nuées ardentes that overran our Burr Point camp in January 1976 detached themselves from the basal avalanche which turned northeast a few km upslope from the camp, swept over the camp and continued out to sea (see Figure 19b and c). We have described the damage to the Burr Point camp when we discussed the 1976 eruption. Another cabin on the northeast coast of the island was completely erased by a strong blast.

Seven lobate hummocky bathymetric features, that morphologically resemble the Burr Point pyroclastic avalanche terrain, can be seen to extend up to 4 km offshore, predominantly on the north, east and south flank of Augustine Volcano (Figure 38, based on NOAA-NOS hydrographic survey H-9073, vicinity of Augustine Island, contoured by John Whitney, USGS). Whitney (personal communication) suspected these features to be submarine flows extending up to 7 to 10 km from the summit vent based on their morphology and seismic reflection profiler data. We do not know if they were emplaced subaerially or submarine but their young age of about 1500 years B.P., based on two C^{14} dates from a soil horizon that directly overlies their landward continuation on the east shore, suggests that sea level was near its present level. Even though the age is a minimum age and the flows could be a little older sea level was probably not much changed, suggesting a submarine emplacement. We will try to

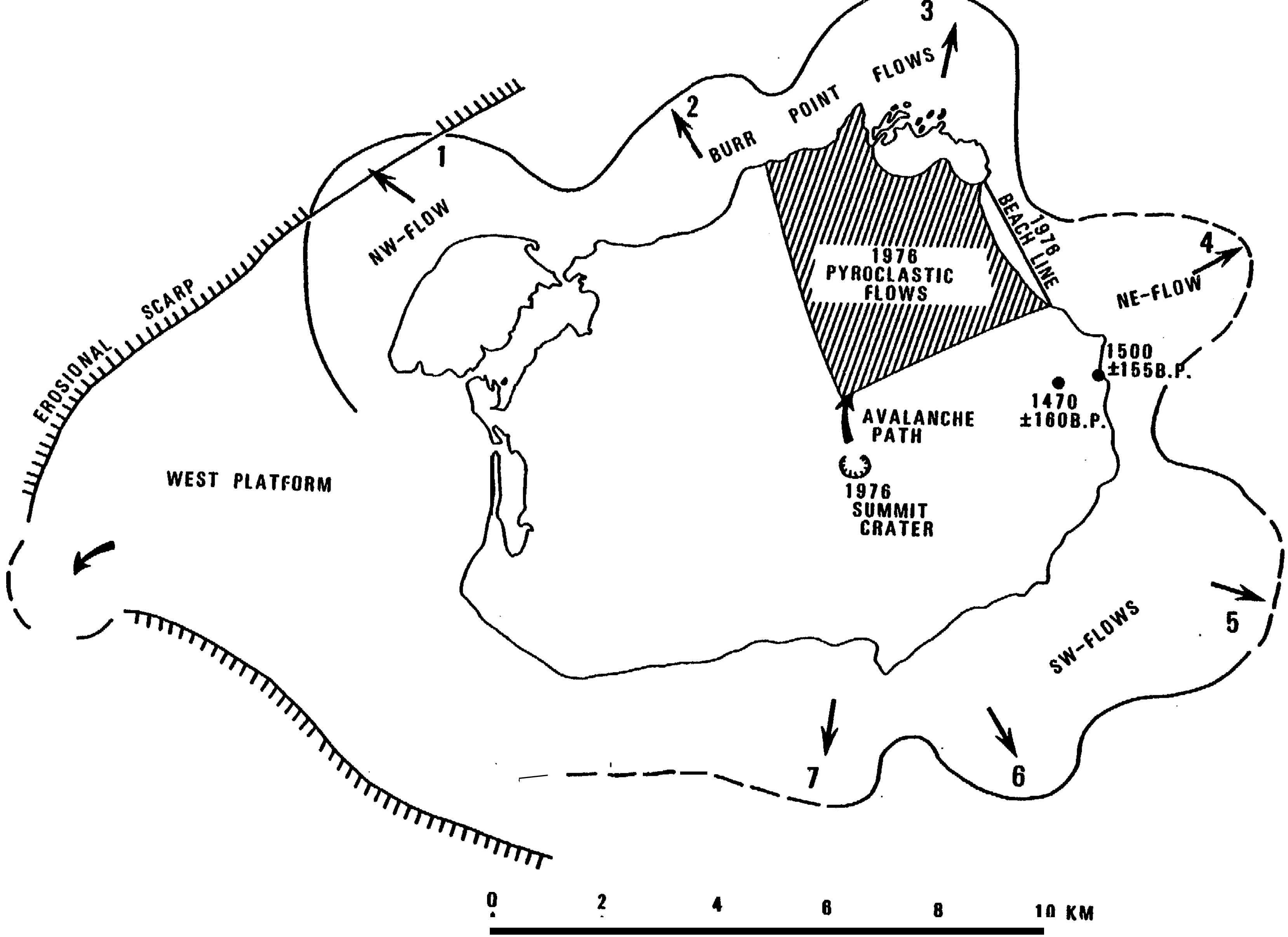


Figure 38. Suspected offshore pyroclastic flow deposits off Augustine Island.

verify the nature of these flows through direct sampling with divers this year.

Submarine counterparts of late Quaternary subaerial pyroclastic flow deposits off the western flank of the 1,400 m high volcano Morne Diablotins on the island Dominica, Lesser Antilles (the next island north of Martinique, where Pelée is located) were recently investigated by seismic reflection profiling and dredging (Sparks et al., 1980a and b). A submarine fan, consisting of block-and-ash flow deposits formed by dome collapse and a welded ignimbrite could be traced as a major ridge (2-4 km wide and 200-400 m thick) to over 13 km (!) offshore at a water depth of 1,800 m. Sparks et al. suggest that this demonstrates that pyroclastic flows can move underwater without losing their essential character and furthermore that the deposit may even be welded. The two papers by Sparks et al. are the only ones known to us on the subject of what happens when pyroclastic flows enter the sea. The fact that they can stay intact for such long distances suggests that there is a good chance that the preliminary identification of the submerged rugged terrain offshore Augustine as pyroclastic avalanches will prove to be correct (Figure 28).

In summary, basal avalanches and associated hot air blasts and nuée ardentes are the major hazards from pyroclastic flows on Augustine Island. The basal avalanches present a hazard to any structure built on the island or in the near offshore area (at least as far as the postulated offshore flow deposits shown on Figure 38 reach). Thermal blasts and nuée ardentes present a hazard on the entire island and to a considerable distance offshore. Both can effectively carry across water for some distance as evidenced by the destruction of ships in the harbor of St. Pièrre during the 1902 eruption of Mt. Pelée. The effective range of the thermal effects is at least twice that of the actual avalanche deposits (Taylor, 1958). The avalanches are generated suddenly and reaction time is extremely short. The distance traveled and the velocity of the flows depends mainly on their volume, given the more or less fixed topography of Augustine Volcano. Small flows may spend themselves before they reach the sea, larger ones may continue offshore. At the seashore the basal avalanche will continue under water while the accompanying nuée ardente will detach itself and then surge rapidly out to sea.

Debris Flows and Flood Deposits

Debris flow and flood deposits are also common on Augustine Island (Figures 3, 7, 8, 11 and 34). Conventionally, this category of deposits would include just the classical mudflow deposits formed by water-saturated masses of debris moving downslope in response to gravity. However, experience with the 1976 Augustine eruptive deposits has shown that surface deposits of pyroclastic flows and tephra are quickly modified by running water from either snow melt or heavy rainfall and the distinction of such reworked material from original mudflow deposits is difficult, especially on aerial photographs of the older eruptive deposits. Thus, the debris flow and flood deposit category includes not only mudflow deposits but also reworked air fall deposits. Criteria for recognition of these deposits include the presence of surface flow lines, natural levees and a lobate distal end.

Debris flow and flood deposits are widespread on Augustine, even for a single eruption cycle. During the 1976 eruptions these deposits formed an almost circular apron surrounding the Augustine vent (Figures

27 top right and 34). Lack of a well defined drainage system on Augustine Island and the presence of a thick snow pack for much of the year further smoothing out the topography, act to produce these circular patterns of debris flow and flood deposits.

The deposits consist of poorly sorted volcanic fragments ranging in size from a fraction of a millimeter to several meters in diameter. Fine-grained clay-sized particles are not found in these deposits, as expected, given the fresh unaltered nature of the detritus. Some of the deposits are crudely stratified, apparently in response to a higher water content, with gradation in fragment size defining the individual beds. Variation in particle size for the pumiceous Augustine ejects cannot be directly correlated with particle weight, since some of the more vesicular pieces can actually float on water. Thus, the presence of large particles within a particular bed does not necessarily indicate a high energy flow regime. Many of the pumiceous rocks show evidence of rounding in these deposits, not unusual considering the soft character of the pumiceous volcanic glass.

Hazards from debris flows and floods on Augustine are primarily related to burial. Mudflows, included within this category, can move with great speed (up to 85 km/h) and cover great distances (over 150 km at other taller volcanoes). Given the velocity and extent of debris flows, no cultural features would be safe from burial on Augustine Island (in 1976 we lost all but 1 of our 5 seismic stations and 2 camps). Debris flows quickly break up upon reaching the water and do not present a hazard to installations offshore Augustine Island.

Tsunamis

Sudden displacement of large bodies of water by impact of a pyroclastic flow into the sea can apparently produce volcanogenic tsunamis at Augustine as we have discussed for the 1883 eruption. Because the waves arrived on the other side of Cook Inlet at low tide little damage was done at English Bay in 1883 even though the maximum run-up was about 10 m.

Based on our 10 year record, earthquakes associated with Augustine eruptions will most likely be too small ($<M_L = 4$) to generate true earthquake-tsunamis which involve actual displacement of the sea-floor.

A submarine explosion of the scale of the 1883. Krakatoa event, which took the life of 36,000 people living along the shores of Sunda Strait when a "push-wave" tsunami radiated from the center of the explosion, is unlikely at Augustine, though possible at a much smaller scale.

Ifa tsunami should be generated at Augustine Volcano, platforms and vessels a few km offshore would probably only experience a relatively mild (<10 m) rise in sea level but low-lying areas of coastal communities along the eastern shore of Cook Inlet from Clam Gulch south (Ninilchik, Happy Valley, Anchor Point, Homer, Seldovia, English Bay) could expect run-ups of at least 10 m, depending on local conditions of shoaling.

Tsunami transit time depends on water depth; the velocity v of a tsunami is $v = \sqrt{g.d}$, where g is the acceleration of gravity and d is the water depth. A tsunami generated at Augustine would cross Cook Inlet to English Bay and Homer in about half an hour.

Lava Flows and Domes

Volcanic domes are formed by viscous masses of magma moving up into a volcanic vent and forming a plug. Due to the high viscosity, domes show little tendency to flow. Continued upward movement of the magma mass may eventually make the dome unstable resulting in dome collapse and pyroclastic flows. Hazards from pyroclastic flows due to dome collapse at Augustine Volcano have been discussed in a previous section. Both, dome formation and partial collapse, are highly probable events during future Augustine eruptions.

Lava flows represent the rather quiet movement of lava out of the volcanic vent and down the flanks of the volcano. Lava flows may bury structures. If a hot lava flow encounters snow, melting may produce debris flows. Due to the high viscosities of Augustine magmas, lava flows are not common on the volcano. In fact, only one massive lava flow (prehistoric, on the north flank of the volcano, labeled L in Figure 27) has been identified on Augustine Island.

Tephra

Tephra, as used in this report, refers to rock of any size erupted into the air by a volcano. The rock may initially be molten magma, but this material quickly solidifies to rock upon entering the air. Based upon this definition, tephra eruptions are gradational to and include pyroclastic flows. However, the term pyroclastic flow is here reserved for the rather special glowing avalanche-ash cloud eruption, while tephra is the more general term used to describe any material thrown into the air by the volcano.

Hazards associated with tephra from Augustine Volcano include impact from falling particles, contamination of air with ash and, closer to the vent, thermal effects associated with hot ash.

Particle size in tephra ranges from less than one millimeter to several meters. Larger fragments, termed bombs (diameter greater than 5 cm) generally fall near the volcanic vent while the smaller lapilli (diameter 5 cm to 3 mm) and ash (diameter less than 3 iron) are carried further from the vent. The finest-grained ash may be injected into the stratosphere by very explosive eruptions and from there be dispersed on a global scale.

Winds strongly affect ash dispersal. As redemonstrated for the 1976 eruption, ash can be spread in opposite defections by surface winds and winds aloft. Some of the very large January, 1976 explosions penetrated the tropopause depositing very fine aerosols and sulfur gases in the stratosphere. Kienle and Shaw (1979) demonstrated an increased turbidity of the stratosphere over Mauna Loa, Hawaii, which decayed in about 5 months following the January Augustine eruption. From trajectory analysis at the 300 mbar (9 km) level Kienle and Shaw further deduced that the bulk of the January 23 plumes were transported along the base of the subpolar jet stream following a southeasterly path over western Canada, across the western United States, into Arizona and then turned northeast over the mid-western states and the Great Lakes, to southeastern Canada and out into the Atlantic. The passage of the plume was seen over Tucson, Arizona at an altitude of 7 ± 2 km in the evening twilight on January 25 (Meinel et al. 1976) and was instrumentally observed over Hampton, Virginia, at 12-14 km altitude on the evening of January 28 (Remsberg et al., 1976). This very long distance transport of ash and sulfur compounds in the atmosphere and stratosphere occurred only for products of the more powerful initial vent clearing eruptions, which injected material to heights of up to 14 km. The later less powerful and less voluminous eruptions ejected plumes to more moderate heights of up to about 6 km, and consequently tephra fall was more localized.

Ash falls from Augustine Volcano can be expected to affect much of the Cook Inlet area from Anchorage, to Kodiak and out to the Gulf of Alaska (Figure 14and Table 3). Ash dispersal and subsequent fall is governed by the prevailing wind direction at the time of eruption. For explosive eruptions, high altitude winds will control the ash dispersal. Figure 39 illustrates the prevailing high altitude winds at Kodiak, the point closest to Augustine Island for which such high altitude wind data is available. Prevailing high altitude winds at Kodiak are from the west and southwest. This wind pattern, transferred to Augustine Volcano, would force Augustine ash across Cook Inlet toward Homer. The lower Cook Inlet area may experience ash falls from Augustine Volcano up to a fewcm in thickness. Heavy local ash falls at Iliamna and the lower Kenai Peninsula communities could be harmful to vegetation and livestock and could also contaminate surface water supplies, making them more acid. Machinery and turbines (aircraft) may suffer from severe abrasion and corrosion. For a more detailed discussion of the effects of ash falls uncultivated areas, we refer the interested reader to Wilcox's (1959) excellent discussions of this subject matter. In his paper he gives a detailed account of the affects of an ash fall over the city of Anchorage in July ?953, associated with an eruption of Mt. Spurr 125 km east of the city and he also discusses the effects of the great 1912 Mt. Katmai eruption on vegetation, livestock and man. The paper contains

SUMMARY OF AUGUSTINE ASH FALLOUT COLLECTED AT VARIOUS ALASKAN NATIONAL WEATHER SERVICE STATIONS AND OTHER SOURCES
FOLLOWING JANUARY 23-24, 1976 ERUPTION

Location	Onto	TIM (AST)	Period of Collection	Collection Area	Weight (gm) of Accumulated Ash	Fallout gm/m^2	Fallout Rate gm/m^2-hr
Anchorage (11th and E Streets)	26 Jan. 1976	19:00	≈ 2 hr (1)	1 ft^2	5.1	54.9	≈27.5 (1)
Cantwell	26 Jan. 1976	15:30	--	--	trace	--	--
	28 Jan. 1976	9:45	--	--	negl.	--	--
	29 Jun. 1976	12:45	--	--	negl.	--	--
McGrath	26 Jan. 1976	?	--	--	trace	--	--
	27 Jan. 1976	?	--	--	trace	--	--
	28-30 Jan. 1976	?	--	--	negl.	--	--
Seldovia	23 Jan. 1976	(after 1st erupt., before second.)	--	~ 1 m^2	62.7 gm (2)	≈ 62.7 (2)	--
	23 Jan. 1976 (after 2nd erupt.)	18:30-19:30	1 hr	.92 m^2	171.5 gm (3)	-- (3)	185.6
	24 Jan. 1976	No observable fallout					--
Talkeetna	26 Jan. 1976	18:10	--	--	trace	--	--
	27 Jan. 1976	17:05	--	--	negl.	--	--
Valdez (downtown)	26 Jan. 1976	15:00	--	9 ft^2	.53	.63	--
Iliamna	23-24 Jan. 1976	?	--		--		--
Homer Spit	23 Jan. 1976	late afternoon (from 16:18 erupt.)	--	--	--		
	6 Feb. 1976	15:00-17:00	--	--			--
Oil Point	29 Jan. 1976	15:00-18:00		--	--		

Following February 1976 Eruption

Homer	6-7 Feb. 1976	16:30-16:00	23.5 hr	1 m^2	12.33	12.33	.52

(1) Collector observed bulk of ash fall between 09:00-11:00 AST, 25 January 1976.

(2) First eruptive event only (see notes on observations).

(3) Second eruptive event only (see notes on observations).

TABLE 3 - (compiled by R. Motyka)

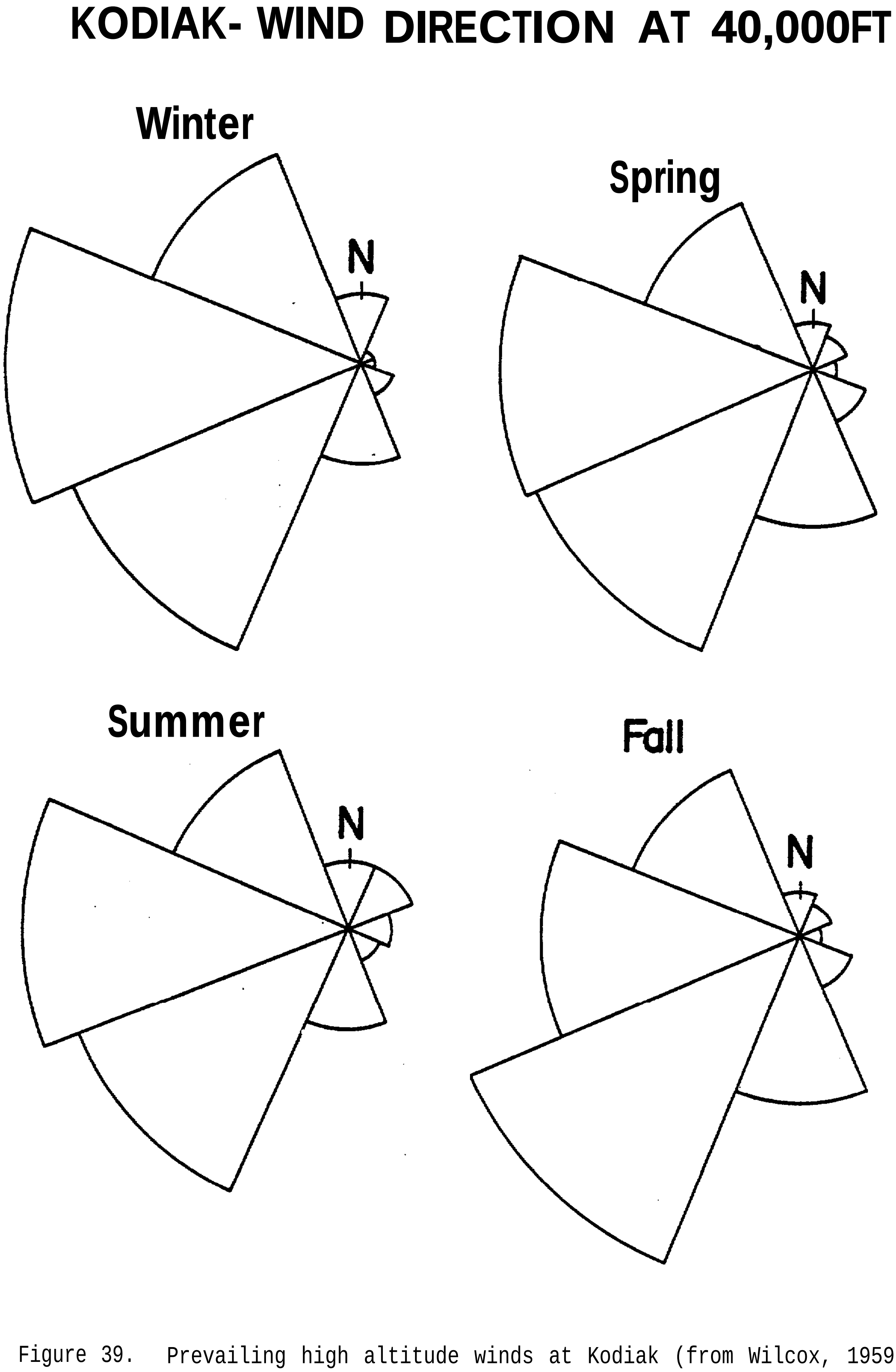


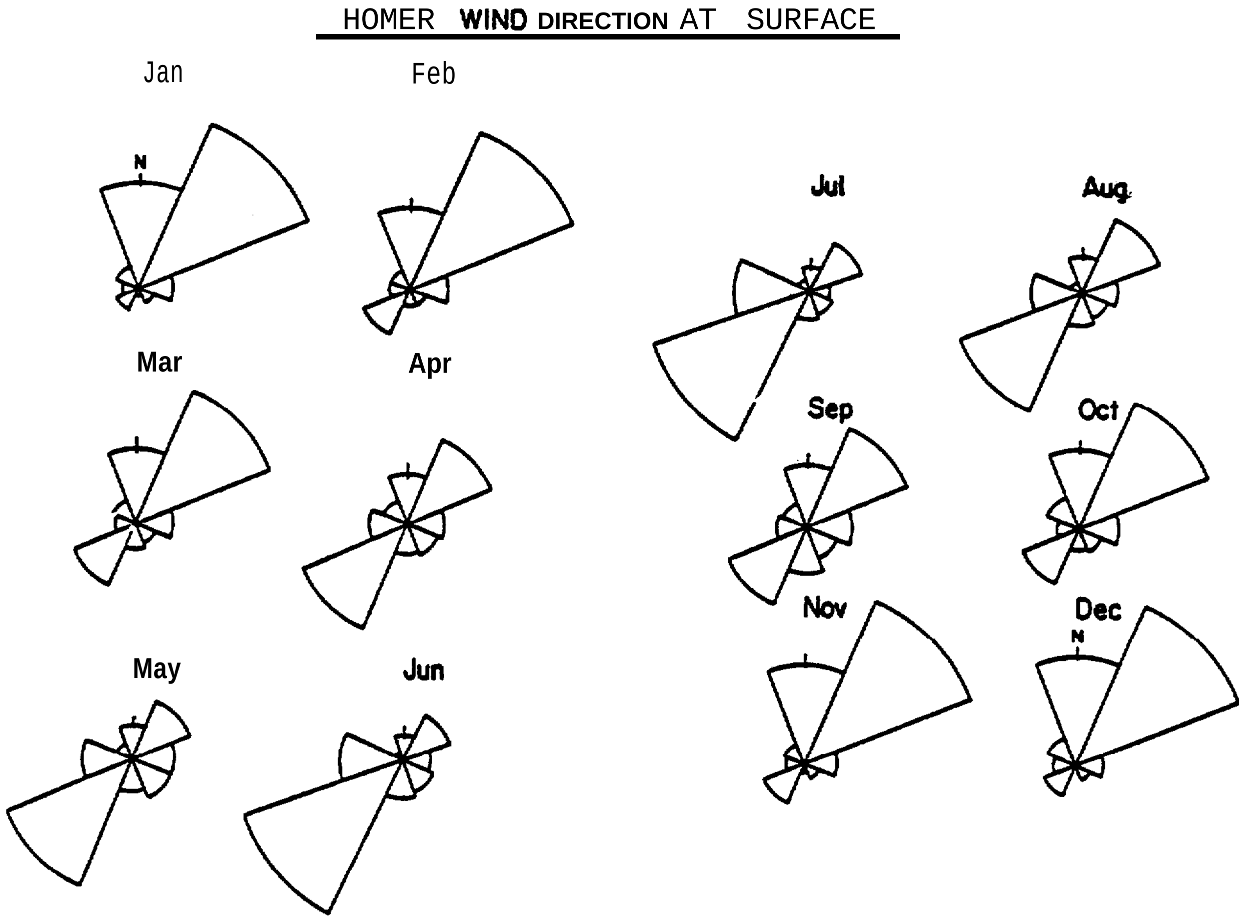
Figure 39. Prevailing high altitude winds at Kodiak (from Wilcox, 1959).

useful tables on the effect of gases on plants (p. 452) and on the effects of gases on humans (p. 443). It is worth noting that for both the Katmai and the Spurr eruptions ash dispersal was principally to the east as we observed for the 1976 Augustine eruptions, confirming the prevailing high altitude flow from the west or southwest, regardless of the seasons.

During the period of heavy ash fall, the air is charged with ash particles that could be harmful, if inhaled. A simple air filter (respi rater) wil 1 remove the ash particles and render the air breathable. In January and February 1976, the air was extremely dusty in the vicinity of Augustine Island, even when the volcano was not in eruption, because strong winds picked up the dust from the island and spread it for tens of km offshore. Figure 40 (top) shows the prevailing surface winds based on Homer wind data, which may not be very representative of Augustine. Surface wind data is badly needed for the island.

Widespread fall oftephra can also have positive effects. Mathisen and Poe (1978) reported that the 1976 Augustine ash falls over the Lake Iliamna, Kvichak waters had almost immediately boosted primary production. The input of phosphorus and silica into the biologic system increased chlorophyll and phytoplankton concentrations and produced a great change in species composition enhancing the productivity of silica utilizing diatoms.

Thorarinsson (1954, p. 62) comments on the complete disappearance of cod on the coast south of Iceland for two days following the ash fall of Hekla in 1947. Perhaps such short-lived migrations of fish do occur near Augustine following extensive tephra deposition offshore, but no one has reported this yet.



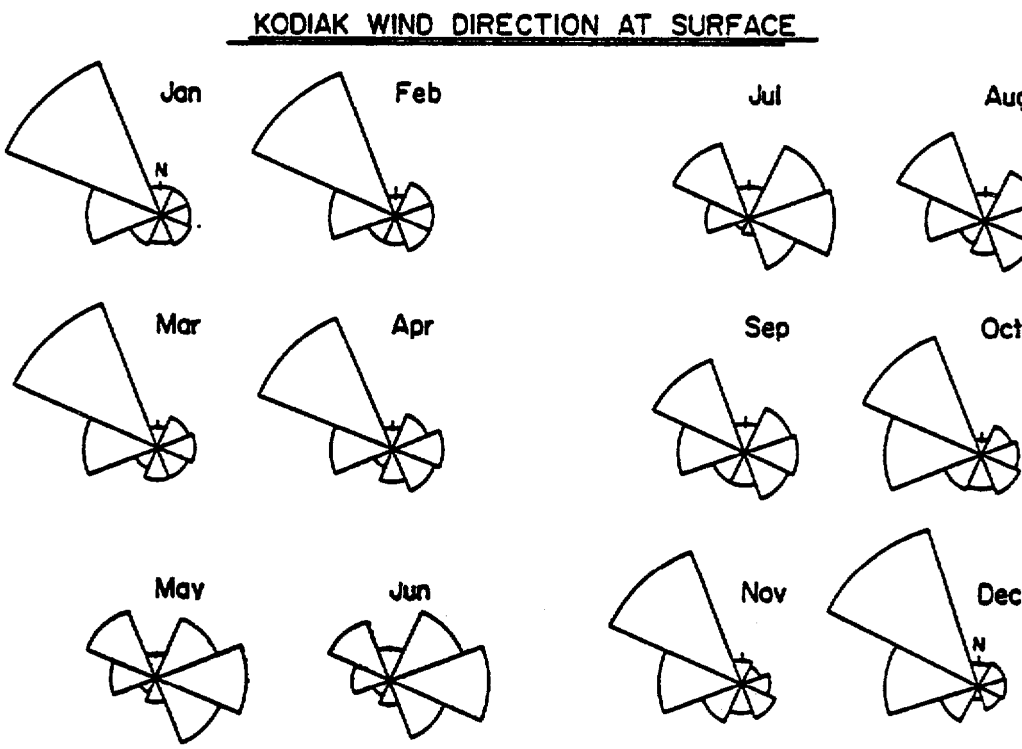


Figure 40. Prevailing surface winds at Homer and Kodiak (compiled from data given in Brewer et al., 1977).

Tephra deposits are widespread on Augustine Island. Generally, the tephra layers are thin, on the order of a few millimeters to a few centimeters around the periphery of the island. Bomb distribution is restricted to the flanks of the volcano where the surface is littered with these large fragments. In 1976, bombs as large as 10 to 15 cm in diameter weighing at least 1 kg fell ballistically through the roof of the Burr Point research station 5.5 km from the summit. Theoretical ballistic considerations (e.g., Wilson, 1972; Fudali and Melson, 1972; Self et al., 1980) considering up to supersonic muzzle velocities suggest that the theoretical vacuum range $R = \frac{V_0^2 \cdot \sin 2\theta}{g}$, where V_0 is the muzzle velocity, θ the ejection angle (max. range for 45°) and g the gravitational acceleration, greatly overestimates the range attained by a projectile and that drag forces drastically reduce the range. Simple oblique ejection of the roof-piercing Burr Cabin bomb from the crater rim would, even at a supersonic muzzle velocity of order 600 m see, not have thrown the bomb that far. We infer that the bomb must have been transported in an oblique trajectory within an eruption column to a considerable height (several km) above the summit to attain that range.

Grain size rapidly decreases with distance from the volcano, For example, the maximum grain size of pumices (density .99 g/cm^3) at Oil Point 35 km north of the volcano was 15 to 20 mm. Damage and injury due to the falling of large blocks are probably restricted to within a radius of about 10 km of the volcano.

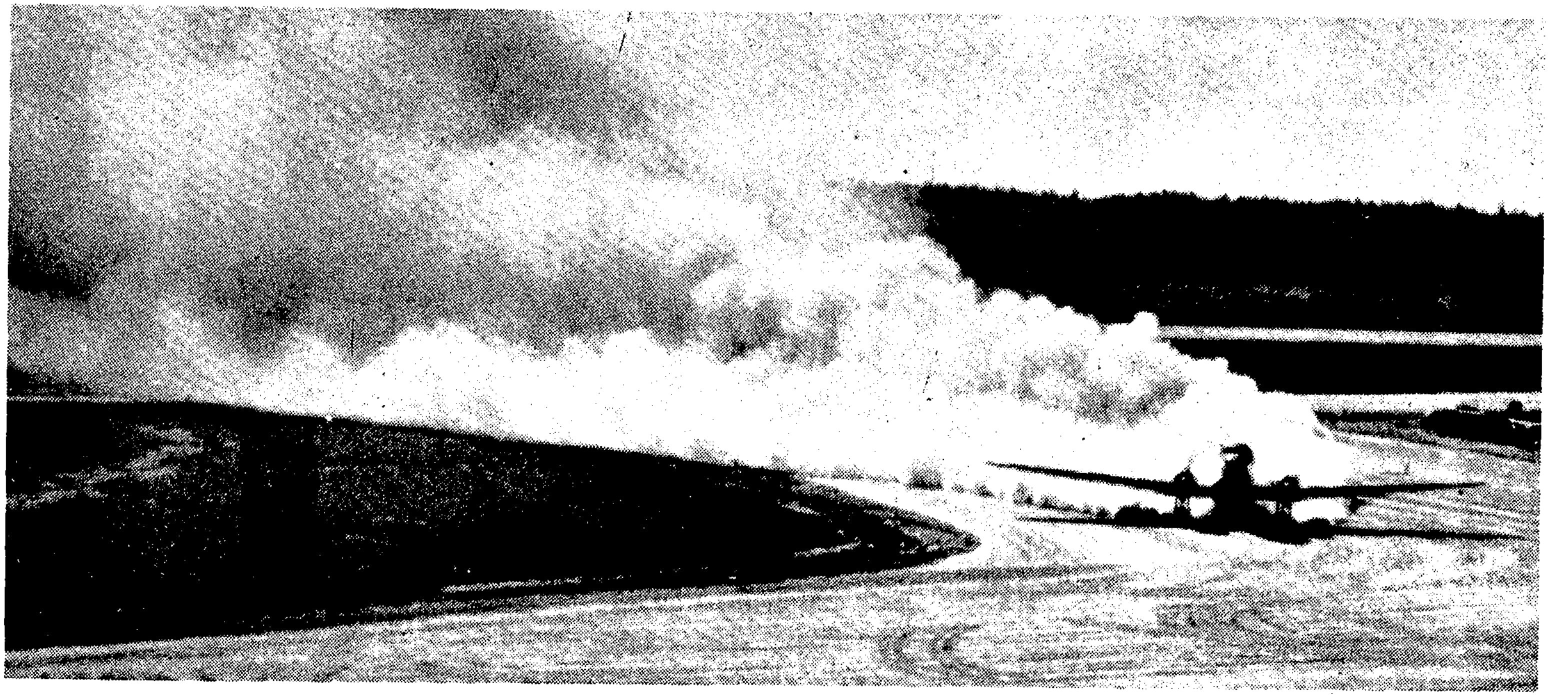
For the dispersal of finer tephra particles we may be able to use Hekla volcano as an analogy. Thorarinsson (1954, reinterpreted by Wilcox, 1959) found that at 3 km distance from the vent 80% of the material was between 0.15 and 5 cm in diameter (maximum size 6 cm), at 30 km 80% it was 0.05 to 0.50 cm diameter (maximum size 1.5 cm) and at 70 km the maximum size was 0.2 cm. The exact ranges depend on local wind conditions, muzzle velocities and height of the eruption column but the example is given here to conveys rough idea of what to expect.

Hazards to aircraft fly"ing near or over an erupting volcano can be quite substantial. Take off and landing on ash covered runways may be temporarily impaired if not completely impracticable due to very low visibility (see Figure 41). Kienle and Shaw (1979) have documented hazards to aircraft penetrating high altitude eruption clouds at large distances (> 100 km) from the erupting volcano in January 1976. One of the January 22 eruptions occurred in the midst of an air defense exercise. The following is an excerpt of a report by two F-4E Phantom Jet pilots who had taken off from Galena on January 22, 1976, bound for King Salmon and penetrated an eruption cloud:

> "The two jets were flying in clouds, cruising at 31,000 feet (9 km). We were still in the weather when suddenly at 14:30 AST (January 23, 00:30 U.T.) the ordinary grey clouds slightly darkened for a moment or two, then there was instant complete darkness. There was no turbulence associated with this darkness. The two jets were flying in close formation about 10 meters apart. Had the lead plane not immediately turned on its lights, the following pilot would have lost contact; he could barely see the lead plane 10 meters away with its lights on. Upon landing in King Salmon the canopy of the aircraft was scoured, and the paint at the wing tips was sandblasted off. Very fine jewelers rouge-colored material was ingested into the cockpit through the engine air intake. The material was sticky and was found in every nook and cranny of the planes."

A second incident concerns three Japanese Airline jet aircraft in route to Tokyo on the afternoon of January 25, 1976 (Mr. K. Noguchi, Japanese Airline, personal communication):

> Cargo flight JL672 took off from Anchorage at 16:00 AST (January 26, 02:00 U.T.). The DC8 was just about to reach its cruising altitude of 33,000 ft (10 km), 25 minutes after takeoff, traveling along air route J501 when it suddenly entered an Augustine ash



Viola Mason

When Mount Spurr, 40 miles northwest of Tyonek, erupted on July 9, 1953, Viola T. Mason, who now resides in Hillman, Michigan, was an air traffic controller at Anchorage International Airport. To commemorate the twentieth anniversary of the big blowup which dumped ash on Anchorage, Miss Mason provided this photo of a plane landing at Anchorage International Airport the day after the eruption. "Each takeoff and landing resulted in near-zero visibility until the dust settled," recalls Miss Mason. "Jet blowers were brought over from Elmendorf Air Force Base to blow the stuff from the runways, but the capricious winds would only blow it back."

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Figure 41. Ash on the runway of Anchorage International Airport from the 1953 Mt. Spurr eruption.

cloud near Whitefish Lake, 25 km southeast of Sparrevohn. Upon landing in Tokyo the scoured center windshield had to be replaced and much ash had adhered to the plane. Slight abrasion damage was found on external radio parts, landing gears and the air-conditioning system, but none of these parts needed to be replaced.

Two other passenger planes, a Boeing 747 and a DC8, also bound for Tokyo and departing within one hour after flight JL672, reported ash suddenly adhering to the planes near Sparrevohn which also caused minor damage but not as extensive as that to the DC8 of flight JL672.

Passenger aircraft along air traffic routes near Augustine Volcano (e.g., Anchorage - King Salmon route) should divert from the volcano when it is in eruption. Unfortunately, diversions are frequently taken in the opposite direction, over the erupting volcano, in order to give the passengers a better view. How dangerous this can be was recently demonstrated, when during eruptions of Sakurazima Volcano in Kuyushu, Japan, on December 18 and 24, 1979, flying bombs cracked the windshields of low flying domestic aircraft. Fortunately, both planes landed safely (SEAN bulletin of the Smithsonian Institution, Vol. 5 (l), Jan. 1980, P. 8).

Large electrostatic charge buildup in active eruption columns can cause severe lightning storms, which may strike passing vessels or aircrafts or block radio communication. We frequently lost our radio VHF signals from seismic stations behind the volcano when eruption columns were well developed. Eruption clouds can easily be seen on land or ship and aircraft based radar (Kienle and Shaw 1979). During summer eruptions forest fires may be started by lightning around the shores of Kamishak Bay.

Visibility can be greatly reduced for short periods of time and at relatively large distances (> 100 km) when an ash laden eruption cloud passes overhead as we described for the towns of Homer and Iliamna during the January 1976 eruptions. For prolonged ash falls, even at moderate ash fall rates, the lasting darkness, if combined with interrupted radio, telephone and electrical services could cause severe psychological stress, perhaps panic as was recently demonstrated during the Mt. St. Helens eruption. Near the volcano such conditions can be extreme and last for days. During many historic eruptions, survivors have reported that day becomes as dark as night. Under these circumstances, evacuation of personal from say a drilling or producing platform offshore Augustine Island maybe quite difficult. Clearing of heavy ash accumulations on roofs of such structures may be necessary to avoid collapse and persons may have to wear respirators for very long periods of time (days).

Volcanic Gases

Large quantities of gas are evolved from juvenile melt during an eruption because of the great decompression that occurs when new melt actually reaches the surface, but active volcanoes also emit gases without the eruption of molten material.

Water is the most common gas, followed by carbon dioxide sulfur compounds (SO_2 and H_2S), carbon monoxide, chlorine and smaller amounts of other gases (Cl_2, F_2, N+ rare gases, $\pm$ H_2) .

The dispersal of volcanic gases is primarily controlled by near-surface winds. Gases are most concentrated near the vent but become rapidly diluted downwind. Odors can often be smelled many tens of km downwind (a table that relates the concentration of various gases to initially objectable odor and to maximum allowable human exposure is given on p. 443, Wilcox, 1959). While SO_2 can be smelled at concentrations of only 1 ppm relative to the maximum tolerable amount of 10 ppm, chlorine is more dangerous as only 0.35 ppm are allowable, yet it can only be smelled at concentrations as high as 3.5 ppm. Near surface wind patterns for Kodiak and Homer (the closest data points to Augustine Island) are shown in Figure 40. This data should be used with extreme care, as it probably does not apply very well for Augustine. Volcanic gases from Augustine Volcano will be spread by surface winds over the lower portion of Cook Inlet. In order to map out the most vulnerable directions we would need average surface wind data for every month of the year at Augustine. During the 1976 eruptions the gases were mainly dispersed east-northeast.

Volcanic gases may be harmful if inhaled in sufficient concentrations for a long time. Hazards from volcanic gases include suffocation, irritation of eyes and respiratory systems and corrosive effects associated with acid compounds. The presence of chlorine or one of the sulfur compounds produces irritation and a burning sensation in the eyes and lungs. However, these gases are mixed with air and if the chlorine or sulfur gas is removed by simple filtration (industrial gas masks work well) the air is safe to breathe. If a mask is not available a wet cloth over mouth and nose does wonders, especially when wetted with a dilute solution of Sodium Bicarbonate (e.g., medicinal powders sold for acid indigestion or baking soda).

Freak accidents sometimes occur in volcanic areas when odorless CO_2 pools in topographic depressions. On February 20, 1979, during eruptions of Dieng (Indonesia), 149 persons were killed by gas containing H_2S and mainly CO_2 which ponded in a low-lying area beside a road. Fleeing along the road from the eruptive activity the people passed the pool and suffocated (SEAN bulletin of the Smithsonian Institution, Vol. 4 (3), March, 1979, p. 5).

Chlorine and sulfur gases are extremely corrosive on metals. Rain water combining with chlorine or sulfur gas can produce acid rains that are harmful not only to metals, but also to vegetation. Acid rains during the 1912 Mt. Katmai eruptions spread to Seward and Cordova and even to Vancouver (B.C.) and Chicago (Griggs, 1922). The bulk of the acid in these rains is sulfuric acid, as SO_2 combines with H_2O in the atmosphere. Dilute solutions of baking soda or alkaline soap help to neutralize the acid and can be used to wash metal objects and irritated skin and eyes.

During eruptions involving new melt, as is the case for all historic Augustine eruptions, the volcano emits large amounts of sulfur dioxide and also substantial quantities of chlorine (Johnston, 1980).

In summary, gas-related hazards from Augustine Volcano are primarily related to corrosive effects of chlorine, sulfur gases and accompanying acid rains. Hazards to health or life from these gases can largely be removed by simple filtration. Corrosion of metallic structures in lower Cook Inlet will be a problem during eruption of Augustine Volcano. The concentration of the gases and hence the level of the hazard is of course greatest near the volcano.

HAZARD ZONES

All of Augustine Island and much of the lower Cook Inlet area will be affected by future eruptions of Augustine Volcano. Hazards to both human life and property are expected during an Augustine eruption. However, the approach to hazard zoning taking in this report follows the example of Crandell and Mullineaux (1978) for Mount St. Helens Volcano and does not distinguish between hazards to life and property. Instead, the hazard zones attempt to describe areas of potential danger from different eruption-related hazards and then assess the hazard in terms of magnitude and expected frequency.

Assumptions

Two key assumptions aremade in the hazard zone analysis:

First, the eruptive pattern for Augustine Volcano in the future will be similar to the past eruptive history. Studies of historic Augustine eruptions reveal a similarity in eruptive style and products. Magma composition, which plays a big role in determining the mode of eruption, has been relatively constant on Augustine Volcano for at least the past 1,500 years, implying a similar eruptive style for the past 1,500 years. Augustine Volcano has erupted several times per century and this active pattern is expected to continue.

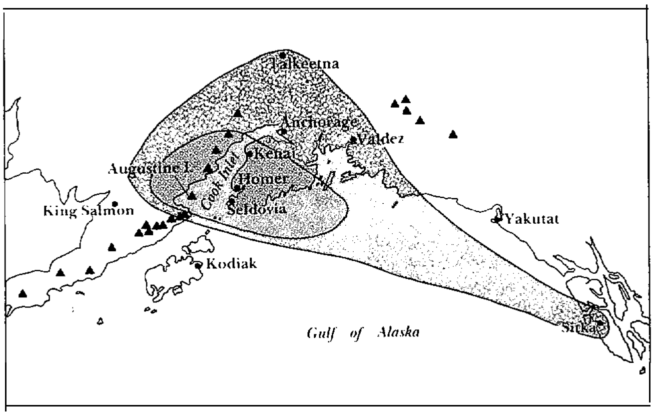
A second assumption involves the regional extent of hazard zones. Data for some types of hazards associated with Augustine eruptions are incomplete or nonexistent. Examples of such data gaps include the extent of pyroclastic flows around Augustine Island and how far the associated hot gas clouds would travel out to sea. The horizontal distances traveled by the hot gas clouds beyond the shore line have never been measured, nor has the offshore extent of the pyroclastic flows been determined. In such cases historical analogues have been selected to model the Augustine hazards. Particular reference is made to the 1902 eruption of Mont Pelée in the West Indies (Anderson and Flett, 1903) and the 1951 eruption of Mount Lamington in Papua (Taylor, 1958). Both of these volcanoes are characterized by pyroclastic flow eruptions and are similar in height to Augustine Volcano and thus should serve as good models for Augustine eruptions.

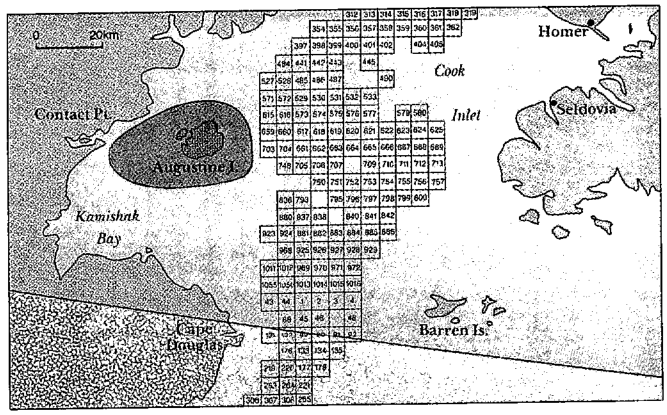
Hazards from Augustine Volcano are principally associated with pyroclastic flows and tephra fall. Hazard zones are shown on Plate 1. Four hazard zones, ranging from low risk to very high risk are distinguished around Augustine Island. Boundaries between the zone are not exact, but instead represent the authors best estimate of the effective range of a given set of hazards. Future work on Augustine eruptive products, particularly offshore deposits, may change the hazard zones shown on Plate 1.

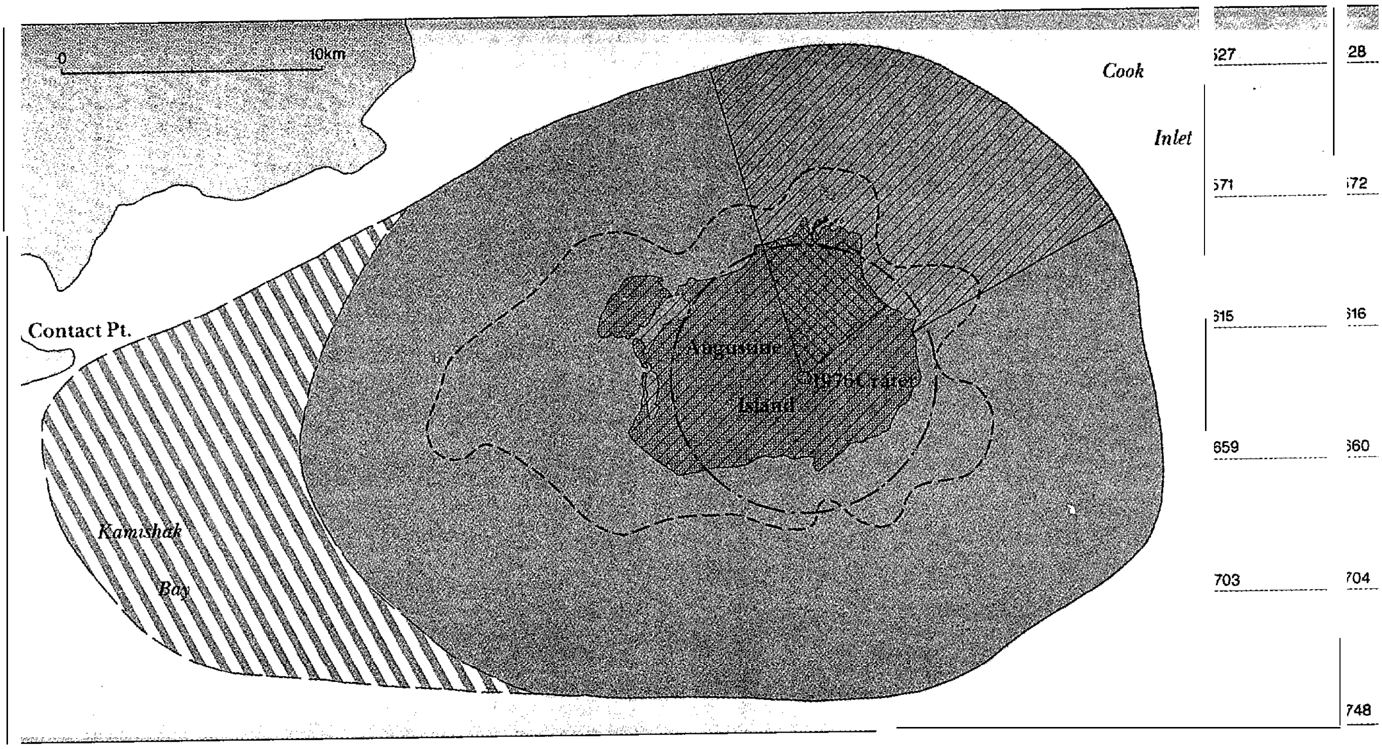
Very High Risk Hazard Zone

A very high risk hazard zone includes all of Augustine Island and an offshore region to the northeast of the island (Plate 1). Within this zone, hazards are associated with pyroclastic flows (nueé ardentes) volcanic bomb fall, mudflows, tephra accumulation and volcanic gases.

Pyroclastic flows are a common feature of Augustine eruptions and should be expected to accompany every eruption of the volcano. Hazards accompanying the pyroclastic flows are associated with both the basal avalanches and the hot ash clouds (nueé ardentes). During historic time, pyroclastic flows have moved down all sides of the volcano, except for the southern flanks (Figs. 7, 8, 11 and 34). However, postulated







Area of very high risk to human life and property associated with falling volcanic bombs, pyroclastic flows, volcanic gases, thick tephra accumulation and mudflows (on or nearshore only).

Area of high risk to human life and property caused by pyroclastic flows, volcanic gases and tephra accumulation. (Extent uncertain in striped area.)

Area nf low risk to human life and moderate risk to property caused by volcanic gases and tephra accumulation.

Area of no risk tn human life and low risk to property caused by volcanic gases and tephra accumulation.

Al-es of no risk to human life or property.

Extent of 1976 pyroclastic flows.

Extent of offshore pyroclastic deposits based nn bathymetry.

Extent of volcanic bomb fall fnr 1976 eruption (Fragments > 15cm diameter.)

Offshore lease blocks.

A Volcanoes,

Plate 1

offshore pyroclastic flow deposits are found to the south of Augustine Island (Plate 1) and thus future pyroclastic flows might extend in any direction from Augustine Volcano. Due to the present crater configuration and the shape of the 1976 dome, the next eruption of Augustine Volcano is expected to initially direct pyroclastic flows down the north flank of the volcano, hence the offshore extension of the very high risk hazard zone shown in Plate 1. Volcanic risk is fairly high at lease blocks 571, 615, 659 and 703 and the latter two should probably not be reoffered for sale; the first two are already sold. Continued eruption and dome removal may subsequently change the direction of pyroclastic flow movement.

A zone of volcanic bomb hazard is shown on Plate 1 as a circle with the center at the 1976 Augustine Crater. The radius of this hazard zone is the distance from the 1976 crater to the Burr Point research station (an area that sustained volcanic bomb damage during the 1976 eruption, as previously discussed). Hazards associated with volcanic bomb fall may extend the limits shown, but the area within the circle (including most of Augustine Island) is subject to heavy volcanic bomb fall.

Mud (debris) flows accompany all eruptions of Augustine Volcano and may continue for several years following an erupting depending on availability of detritus on the slopes of the volcano. Mudflows may develop on any portion of Augustine Island and extend for short distances into offshore areas.

Accumulation of new material within the very high risk hazard zone (Plate 1) is associated mainly with the deposits of pyroclastic flows and, to a lesser extent, with ash fall from eruptive clouds. During the 1976 eruption of Augustine, pyroclastic flows deposited material tens of meters deep on the northeastern portion of the island (Fig. 34) while tephra accumulations from the normal ash fall formed deposits less than

10 cm thick at the periphery of the island. Accumulation of air fall tephra is largely controlled by the prevailing winds. For areas close to the volcano, such as the high risk zone shown in Plate 1, deposition of air fall tephra will be controlled by surface wind directions. The surface wind data available for Homer and Kodiak (Fig. 40) is probably not applicable for Augustine Volcano because in both cases the wind data might be affected by severe topography. Our experience during the 1976 eruption suggest that all sectors of the volcano will be affected by tephra fall with the northeastern and southwestern sector receiving most of the accumulation. Volcanic gas dispersal is also controlled by surface winds within the high rish area and should follow the same pattern as air fall tephra.

High Risk Hazard Zone

A high risk hazard zone characterizes the immediate offshore area of Augustine Island (Plate 1). The outer limit of this hazard zone is based on the presumed extent of offshore pyroclastic flows. On the western edge of Augustine Island a broad submarine platform (Plate 1) may represent submerged pyroclastic flow deposits or an old erosional bench. Because of the uncertainty regarding the character of this terrain, the extent of the high hazard zone in this region is uncertain. The western limit for the high hazard zone on Plate 1 is drawn assuming that this terrain represents pyroclastic flow deposits. If subsequent work reveals that the western submarine platform is not composed of pyroclastic flow deposits, the western extent of the high risk hazard zone shown on Plate 1 would be reduced.

Other offshore deposits are apparent on the bathymetry around Augustine Island (Plate 1) and their lobate form and rough topography suggests they are probably pyroclastic flow deposits. Pyroclastic flows did travel offshore during the 1976 eruption of Augustine Volcano and Sparks et al., (1980a) documented submarine pyroclastic flow deposits offshore a volcano on Dominica in the West Indies. Thus, pyroclastic flows can travel for some distance underwater and the bathymetry outlined on Plate 1 very likely does represent pyroclastic flows from Augustine Volcano that moved offshore for some distance.

Hazards within the high risk hazard zone (Plate 1) are associated with pyroclastic flows, tephra accumulation and volcanic gases. Hazards from pyroclastic flows are related not only to the basal glowing avalanches that account for most of the deposition of debris but also to the thermal and blast effects from the nuée ardente that rises above the glowing avalanche. Hazards due to hot blasts from the hot ash cloud extend in a sear zone well beyond the termini of glowing avalanche deposition. At Mont Pelée and Mount Lamington the hazard zone associated with the hot ash cloud extended up to twice the distance from the crater to the distal ends of the basal avalanche deposits (Anderson and Flett, 1903; Taylor, 1958). The limit of the high risk hazard zone shown on Plate 1 is taken to be three times the extent of the pyroclastic basal avalanche deposits. Tephra accumulation within the high risk hazard zone will vary in thickness from meters (basal avalanche deposits) to less than a few tens of centimeters (air fall tephra). All sectors of the volcano within this zone will be affected by volcanic gas or air fall tephra as controlled by surface wind dispersal.

Moderate Risk Hazard Zone

A zone of moderate risk hazard covers most of the lower Cook Inlet and much of the Kenai Peninsula (Plate 1, insert). Hazards within this zone are due to tephra accumulation and volcanic gases. At these distances from Augustine Volcano, tephra accumulation will result from air fall and the distribution will be controlled largely by high altitude winds. Figure 39 gives the high altitude wind pattern for Kodiak (the weather station closest to Augustine Island with high altitude wind data) and shows the dominant westerly high altitude wind flow. These persistent westerly winds account for the tephra dispersal pattern over the lower Cook Inlet shown on Plate 1. The outer limit of the moderate risk hazard zone shown on Plate 1 is approximately the limit of one millimeter of tephra accumulation during the 1976 eruption of Augustine Volcano. Moderate volcanic gas concentrations are expected within the zone of moderate volcanic risk. The major hazard associated with these relatively low concentrations of volcanic gas is the corrosive effect on metals.

Low Risk Hazard Zone

A zone of low risk hazards associated with tephra accumulation and volcanic gases from Augustine Volcano covers much of south-central Alaska (Plate l). This hazard zone coincides with the area of trace tephra accumulation from the 1976 eruption of Augustine Volcano. Distribution of tephra and gas within this zone is controlled by the high altitude westerly winds. Tephra accumulations are expected to be less than one millimeter and low concentrations of volcanic ash and gases will result in minor corrosion to metals.

Data Gaps

Several data gaps were found during the volcanic hazard assessment of Augustine Volcano. Some of the data gaps are currently being filled while others are not being studied. Aside from the historic record, little tephrachronologic data is available on the frequency of eruptions of Augustine Volcano. Very preliminary data (Fig. 36) suggests the recurrence interval is becoming shorter. However, without confirmation in the prehistoric record this intriguing suggestion cannot be evaluated. C^{14} geochronology is currently being done on paleosoils interbedded with tephra from the northeast side of Augustine Island and this study will furnish some data on the problem of recurrence interval. To properly study prehistoric Augustine eruptions, detailed tephrachronologic studies should be done at sites in Kamishak Bay around Augustine Volcano.

Another data gap involves the extent of offshore pyroclastic and debris flows and the glacial history of Augustine Volcano. Postulated offshore flows, based on bathymetry, are shown on Plate 1. It is not certain that these offshore areas represent flows. Sampling of these offshore areas will be attempted by divers in 1980 and if successful we should be able to assess the extent of offshore flows.

Wind data is not available for Augustine Island and the dispersal of volcanic gas and ash from Augustine Volcano must utilize high altitude wind data from Kodiak {Fig. 40) or surface wind data from either Homer or Kodiak (Fig. 41). High altitude winds probably show little variation over the relatively short distances between Kodiak and Augustine Island. However, surface winds show considerable variation over relatively short distances due to the influence of surface topography and thus, the application of surface wind data from Homer or Kodiak to Augustine

Island is probably not valid. Surface wind data from Augustine Island is very much needed to assess the dispersal of low altitude ash and volcanic gas from eruptions of Augustine Volcano.

Some eruptions of Augustine Volcano, such as the 1883 eruption, produced tsunamis of considerable magnitude (Kienle and Forbes, 1976). Hazards from eruption-related tsunamis have not been studied in the current hazard assessment and warrant future work.

VOLCANIC ERUPTION PREDICTION AND MONITORING

Augustine will certainly erupt again and it is likely that the eruptions will be similar in magnitude and style to the previous ones. We base this prediction on the constancy of volume and geochemistry that has been observed for the past 5 historic eruptions and the composition of tephra back to 1,500 B. P. Pyroclastic flow activity and lava dome formation will probably accompany the next eruption with widespread ash falls affecting much of the lower Cook Inlet region, including both the eastern and western shores. The duration of eruptive activity is likely to be less than 1 year and most intense only during a few months.

We have discussed the geophysical precursors to eruptions that are commonly monitored on other volcanoes, i.e., seismicity, deformation, subterranean mass movement, changes in the electric and magnetic fields, changes in heat flux and fumarole temperatures, and changes in the geochemistry of the gases emitted from the volcano.

Since 1970, we have tried most of these methods on Augustine Volcano, except deformation, and found seismicity the most reliable predictor tool. As we discussed above, the January 1976 eruptions were preceded by eight months of low-magnitude microearthquake activity, with a major earthquake swarm of larger magnitude events signaling the main set of eruptions on January 23, 1976 that cleared the vent only hours later. A few preliminary explosions occurred before this earthquake swarm. Contrasting this sequence of events with the recent Mt. St. Helens eruptions, seismicity at Helens increased dramatically about 2 months prior to the catastrophic May 18, 1980 eruption, with March 20 marking the date of the first significant earthquake, of magnitude ML = 4.1. Frequent large-magnitude events (M_L = 4-5.5) and occasional harmonic tremor, indicating magma movement at depth, were recorded during the 2 months prior to May 18 but no significant seismic events signaled the cataclysmic blast of May 18, which had an extremely sudden onset. To our knowledge at this time, the only other important precursor to the May 18 event was rapid uplift of an area just below the crater on north side of the volcano, beginning in late April - as much as 6 m between April 24 and 29 (Scientific Event Alert Network - SEAN, Smithsonian Institution, Washington, D. C., 5(4):3).

For the future, in addition to continuing to operate the 4-station island-based seismic array we are planning to begin geodetic monitoring of Augustine Volcano to measure deformation. Hopefully, continued geophysical monitoring of Augustine Volcano will allow us to anticipate, if not predict the next eruption.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of Dr. David A. Johnston to the studies of Augustine Volcano. Much of the petrologic data on the 1976 eruptive products was collected by Johnston as part of his Ph.D. dissertation at the University of Washington. In addition, he contributed to the hazard studies and the collection of Augustine volcanic gases by Johnston furnish the only direct evidence on the gas composition. David Johnston lost his life during the recent (1980) eruptions of Mount St. Helens and with his passing Alaska volcanology lost a real friend.

The contributions of D. J. Lana, R. B. Forbes, H.-U. Schmincke, D. B. Stone, J. Whitney and other students of Augustine's volcanism are gratefully acknowledged.

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APPENDIX

PHOTOGRAMMETRIC MAPPING OF THE SUMMIT REGION AND NORTHEAST SECTOR OF AUGUSTINE VOLCANO

APPENDIX

Photogrammetric Mapping of the Summit Region and Northeast Sector of Augustine Volcano

The U.S. Geological Survey Iliamna Quadrangle Map B-2 of Augustine Island is based on aerial photography flown in 1957 and field annotated in 1958. The 1963/64 and 1976 eruptions altered the volcano, particularly the summit region, significantly. After the 1964 dome intrusion the summit was 279 ft. (85 m) higher than shown on the Quadrangle map. During the 1976 eruption 204 ft. (62 m) were lost from the summit.

With funding from these contracts a new post-1964 but pre-1976 topographic map was prepared of the Augustine summit region above the 2,500 ft. contour line, based on photography flown by North Pacific. Aerial Surveys, Inc., Anchorage, on June 16, 1973. Figure Al shows a photographic reduction of this map.

The 1976 eruption again altered the summit region dramatically. New vertical photography was acquired through North Pacific Aerial Surveys and a new topographic map of Augustine's summit above the 2,500 ft. contour line was prepared at the same scale as the previous map. Figure A2, based on August 21, 1976 photography, shows the dramatic changes that took place during the 1976 eruptions, which resulted in the removal of the 1964 lava dome, the creation of a large crater which was subsequently partially filled by a new dome intrusion which took place between February and April, 1976.

Figure A3 is a photographic reduction of a new topographic map of the northeast sector of Augustine Island, most heavily altered by pyroclastic avalanches during the 1976 eruptions. The original maphasascale of 1:10,000 and is based on photography acquired by North Pacific Aerial Surveys on August 21, 1976.

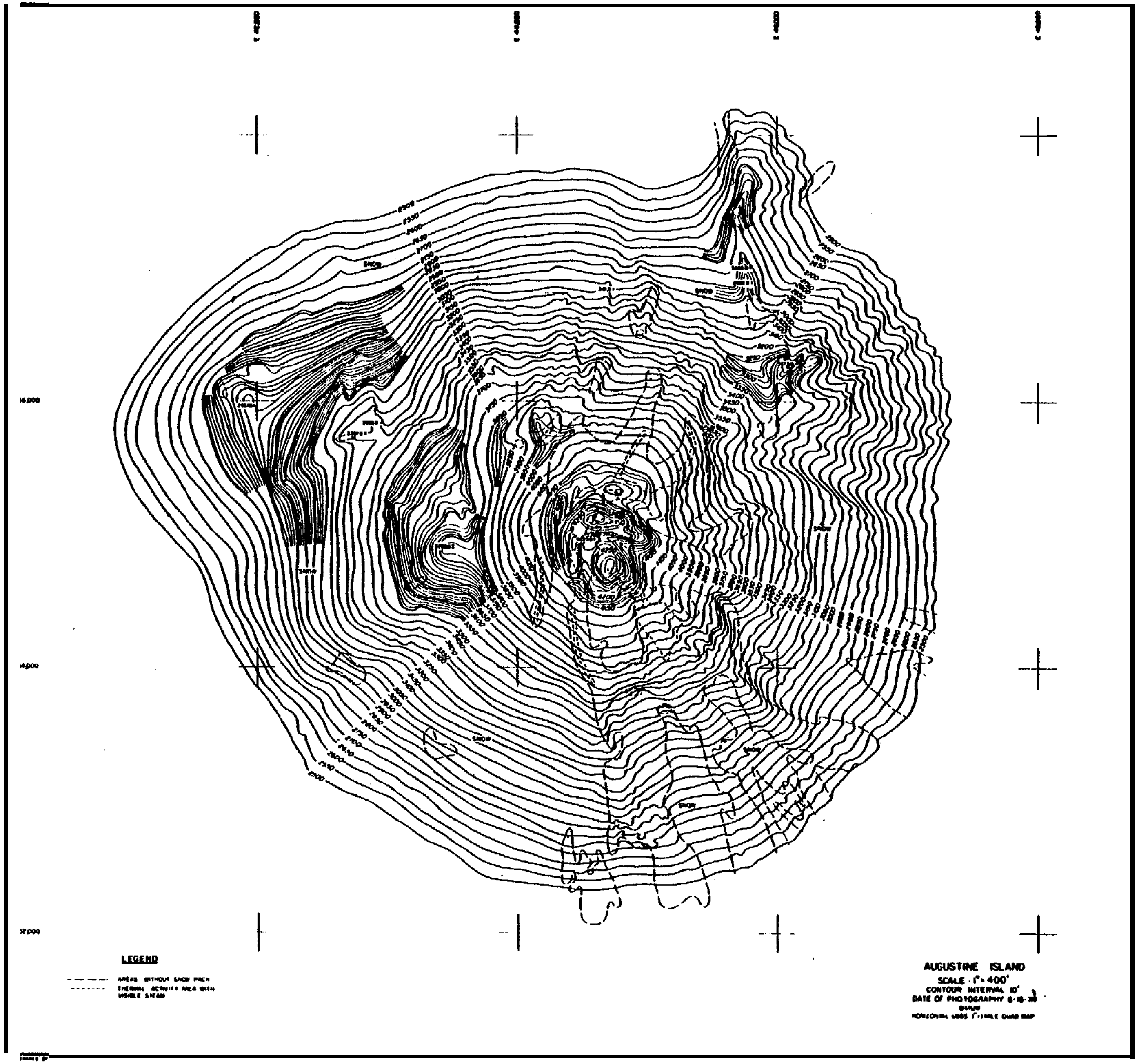

Figure AI. Topographic map of Augustine Volcano's summit region based on aerial photography taken on June 16, 1973, i.e.. post 1963/64 eruption but pre-1976 eruption. The contour interval is 10 ft. and the distance between tickmarks is 2,000 ft. (prepared for the Geophysical Institute of the University of Alaska by North Pacific Aerial Surveys, Inc., Anchorage.

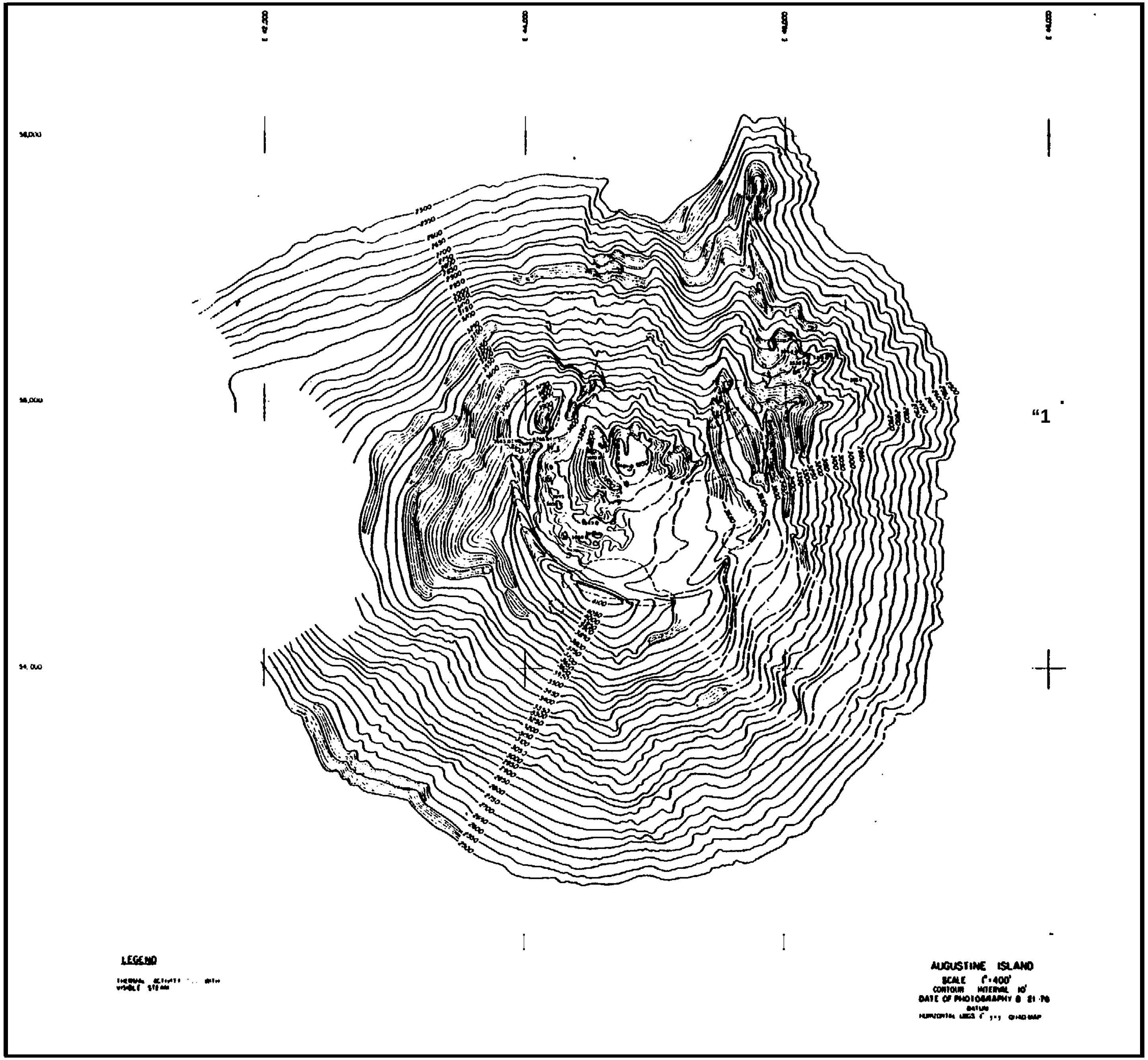

Figure A2. Topographic map of Augustine Volcano's summit region based on aerial photography taken on August 21, 1976, I.e., post-1976 eruption. The contour interval is 10 ft. and the distance between tickmarks is 2,000 ft. (prepared for the Geophysical Institute of the University of Alaska by North Pacific Aerial Surveys, Inc., Anchorage.

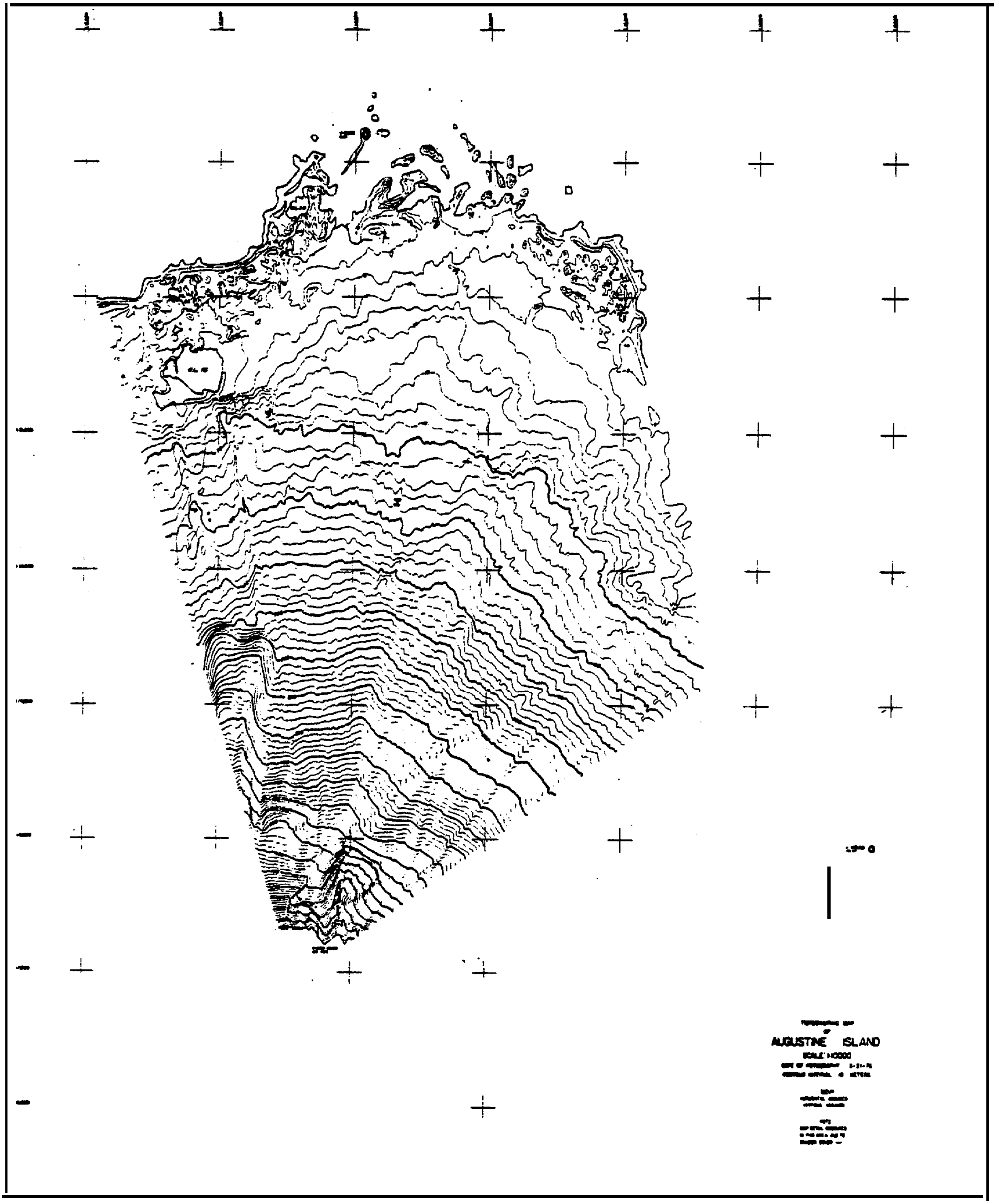

Figure A3. Topographic map of the northeast sector of Augustine Volcano based on aerial photography taken on August 21, 1976, i.e., post-1976 eruption. The contour interval is 10 m and the distance between tickmarks is 1000 m (prepared for the Geophysical Institute of the University of Alaska by North Pacific Aerial Surveys, Inc., Anchorage.